CORRELATION AND STRATIGRAPHIC ANALYSIS OF THE BAKKEN AND SAPPINGTON FORMATIONS IN MONTANA

A Thesis

by

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ABSTRACT

The Upper Devonian-Lower Mississippian (Late Fammenian-Tournaisian) Bakken Formation in the Williston Basin is one of the largest continuous oil fields in the U.S. The upper and the lower shale members are organic rich source rocks that supplied oil to the middle member, which is reservoir rock. Although the oil-producing Bakken Formation has been intensely studied in the Williston Basin, the lateral relationship between the Bakken Formation and the coeval Sappington Formation in western Montana remains cryptic. This study correlates the Sappington Formation in western Montana with the Bakken Formation in the Williston Basin in northeastern Montana. It clarifies the lateral relationship between these two units, and extent of their members across Montana and, the causes of these thickness variations. This study utilized 675 well logs (mostly gamma ray, caliper, sonic, density, neutron, resistivity logs) to make multiple E-W and N-S cross sections and isopach maps. Also, seven outcrops of the Sappington Formation in southwestern Montana and five Bakken Formation cores in the Williston Basin were tied to the subsurface data.

Variations in the distribution of the Bakken/Sappington Formation were caused by eustatic changes and local epeirogenic uplifts. The Bakken/Sappington Formation is thickest in the depressions in southwestern and the northeastern Montana, the Central Montana Trough and the Williston Basin in Montana. The Bakken/Sappington Formation is thin coincident with major structural uplifts that were active during the Late Devonian, such as Yellowstone Park Uplift, Bearpaw Anticline, Scapegoat-Bannatyne Anticline and Nesson Anticline. Devonian strata are difficult to identify in the

subsurface of south-central Montana making the Bakken/Sappington correlation problematic in this area. The Lower Bakken/Sappington Member thickness is 15 ft (4.6 m) in northeastern and southwestern Montana. The Lower Bakken/Sappington Member is more continuous in western Montana than the other Bakken/Sappington Members. The Middle Bakken/Sappington Member is thickest (~55 ft; 16.7 m) in the northeastern Williston Basin and in the Central Montana Trough (~50 ft; 15.2 m). The Middle Bakken/Sappington Member was less affected by the tectonics and it is present from northwestern to northeastern Montana, except in far northwestern and central Montana. The Upper Bakken Member (~5-15 ft; 1.5 m-4.6 m) is the most continuous unit in the Williston Basin, as the Bakken Members show onlapping relationship that makes the distribution of each younger member greater. However, the Upper Bakken/Sappington Member is absent west of the Central Montana Trough due to basin inversion and it is also absent in far northwestern and central Montana as a result of the erosion or nondeposition caused by the local uplifts. Transgressions were responsible for the deposition of the upper and the lower black shales in offshore marine environments, whereas the Middle Bakken/Sappington Member was deposited during regression and records multiple offshore marine to tidal environments.

DEDICATION

To my lovely mother, Nebahat Adiguzel and father, Samil Adiguzel

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I would like to express my sincere gratitude to all those people who somehow contributed to this research. First of all, I would like to thank the Turkish Petroleum Corporation for funding my education. I could not make my dream alive without their support. I also would like to express my deep gratitude to my lovely family for their continuous encouragement. Without their faith and their love, I could not have come this far.

I want to acknowledge my co-advisors Dr. Mike Pope and Dr. Walter Ayers for the suggestions and contributions to my research. I thank them for teaching me and for supporting me.

It is not possible to skip two names here: George Grader and Ted Doughty! I am thankful to them for all their invaluable input and mentorship. It is a great pleasure to have them during my journey. I don't think my work could be completed without our discussions and their patience and suggestions.

I want to thank Sebnem Dilaveroglu. It is always great to have her nearby during my hard times in research. I am grateful to God for giving me a great friend like her. I also owe special thanks to Orhan Mehmetoglu. He has always been there for me. He is another reason to feel how much God loves me. I am deeply grateful to Orhan for his endless patience, affection, and support. I would not even imagine finishing my research without his help.

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1. INTRODUCTION

The Upper Devonian-Lower Mississippian (Late Fammenian-Tournaisian) Bakken Formation in the Williston Basin extends from North Dakota and Montana in the United States to Saskatchewan and Manitoba provinces in Canada (Christopher, 1961; Meissner, 1978; LeFever, 1991; Smith and Bustin, 2000; Kreis et al., 2005). The Bakken Formation is composed of three informal members: the lower shale member; the middle calcareous-dolomitic sandstone and siltstone member; and the upper shale member (Christopher 1961; Smith and Bustin, 1996). The shale members are source rocks for conventional hydrocarbon production from the middle member reservoir (USGS, 2008). The shale members are also productive intervals as unconventional hydrocarbon resources (Pollastro et al., 2008). The Bakken Formation is thought to be one of the largest continuous oil fields in the U.S. with 3.65 billion barrels of undiscovered oils, 1.85 trillion cubic feet of associated-dissolved natural gas, and 148 million barrels of natural gas liquids (USGS, 2008).

Deposition of the Bakken Formation began during the Upper Devonian transgression in the Williston Basin and across the Rocky Mountain shelf (Peterson, 1986). Late Devonian strata occur across much of Montana (Sloss and Laird, 1947) and southern Canada, but different names are used to describe the strata in these areas. For example, the Bakken Formation in the Williston Basin, the Exshaw Formation in Alberta, and the Sappington Formation in southern Montana (Grader et al., 2011).

The Famennian-Tournaisian Sappington Formation in western Montana (Sandberg, 1963; Gutschick et al., 1962) was deposited unconformably over the Three

Forks Formation, and it is unconformably overlain by the Lodgepole Formation (Gutschick et al, 1962). The Sappington Formation is composed of upper and lower shale members with a middle calcareous, siltstone member (Gutschick et al., 1962), and it is coeval to the Bakken Formation in the Williston Basin (Nordquist, 1953). Although the oil-producing Bakken Formation in the Williston Basin has recently been intensely studied (Christopher, 1961; Holland et al., 1987; LeFever et al., 1991; Smith and Bustin, 1996; Pollastro et al., 2008; Alexandre et al., 2011), the lateral relationships between the Bakken and Sappington formations across Montana are not well known. Better understanding the relationship between the Bakken Formation in the Williston Basin and the coeval Sappington Formation in western Montana is crucial for future hydrocarbon exploration.

1.1.Objectives

The main objective of this study is to correlate and clarify the regional extent of the Bakken/Sappington Formation in Montana. Regional thickness variations and distribution of the Bakken/Sappington Formations were determined. The lithology and the depositional environment of the Bakken/Sappington Formations and their relationship with overlying and the underlying formations were also described in this study.

1.2. Methods

This study integrates wireline logs, cores of the Bakken Formation and outcrops of the Sappington Formation (Figure 1). Raster logs for 675 wells, comprised mostly of gamma ray (GR), spontaneous potential (SP), sonic, and resistivity surveys, were used for this project. Regional thickness variations of the Bakken/Sappington Formations were studied by constructing multiple N-S and E-W cross sections and isopach maps based on subsurface data, using Petra© software. Seven outcrops of the Sappington Formation in southwestern Montana at Lone Mountain, Logan Gulch, Sappington, Dry Hollow-Milligan Canyon, Brown Back Gulch, Hardscrabble Section and Beaver Creek (Figure 1) were described to clarify the lithology of the Sappington Formation and its contact relationships with underlying and overlying units. The outcrops were characterized with a hand-held gamma ray scintillometer (Grader et al., 2011) to tie into the subsurface data to understand the continuity of the Bakken/Sappington members. Five Bakken Formation cores in USGS Denver Core Storage facility were described, bed-by-bed, and the descriptions were integrated with well log data to delineate lithofacies and to assess contacts with adjacent strata.

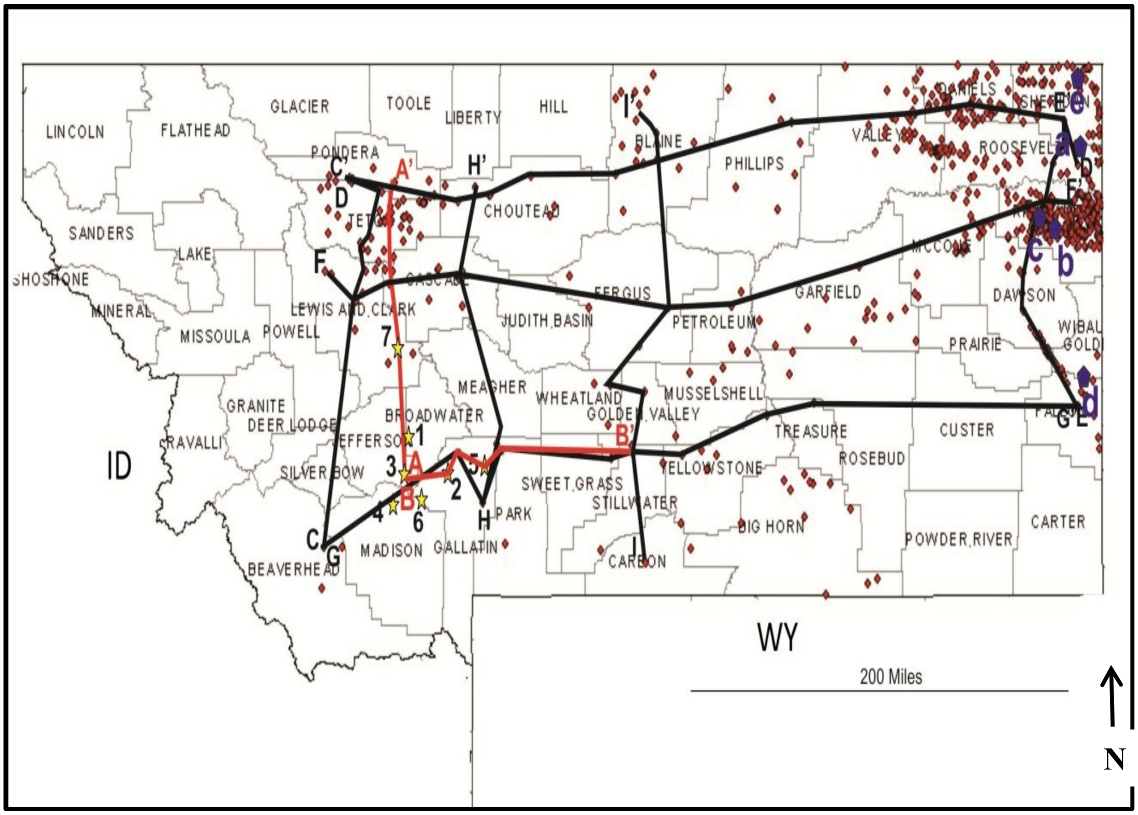

Figure 1. Location of wireline logs (red dots), cores (purple stars) and outcrops (stars) 1-Lone Mountain, 2-Logan Gulch, 3-Milligan Canyon, 4-Brown Back, 5-Hardscrabble, 6-Sappington, 7-Beaver Creek). (a) 1 Big Sky well (b) 1-4 Williams well (c) 44-24 Vaira well (d) A-1 Stark well (e) 5H Joyes State well. The red lines show outcrop-to-log correlation and the black lines show log-to-log correlation data. See Appendix A for well symbols.

1.3. Tectonic Setting

The Upper Devonian-Lower Mississippian Bakken Formation was deposited throughout the Williston Basin (Figure 2a) an intracratonic basin that extends from northern United States (North Dakota, South Dakota and Montana) to southern Canada (Saskatchewan, Manitoba). It encompasses approximately 300,000 square miles with approximately 143,000 square miles in the U.S., totaling 200,000 cubic miles of sedimentary rock volume (Peterson, 1995; Pollastro et al, 2008).

As a result of the overall tectonic stability, the Williston Basin is relatively simple basin that began to subside during the Late Ordovician (Gerhard and Anderson, 1988; Pollastro et al., 2008). The Bakken Formation was deposited during the Kaskaskia supersequence (Gerhard et al., 1982, Hester and Schmoker, 1985) which formed multiple 2nd to 3rd order transgressive-regressive cycles in the Devonian and Mississippian Periods. An unconformity between Upper Devonian and Lower Mississippian strata indicates Devonian strata were uplifted along the Williston Basin flanks, and the margins of the basin were exposed to erosion whereas deposition in the deeper parts of the basin was uninterrupted (Sandberg, 1964; Lefever, 1991). Another angular unconformity developed between the Late Mississippian to Early Jurassic time, when Paleozoic strata were tilted, and the northeastern part of the basin was more eroded than the southern region. Jurassic and Cretaceous marine strata were deposited unconformably over an eroded Paleozoic surface (McCabe, 1959; Lefever, 1991). Paleozoic strata record predominantly carbonate deposition in the Williston Basin, whereas Mesozoic and Cenozoic strata are characterized by siliciclastic rocks (Lefever, 1991).

The Nesson, Billings, Cedar Creek, and Little Knife Anticlines are important structural features in the Williston Basin, which were produced by structural deformation during Phanerozoic Eon (Webster, 1984; Heck et al., 2002). Other important structural features in Montana are described below (Figure 2b).

The Central Montana Trough formed during deposition of the Mesoprotozoic Belt Supergroup. It was reactivated to affect distribution of the Paleozoic-Mesozoic sedimentation, and was filled with carbonate, evaporite, and fine-grained siliclastics units during the Paleozoic (Peterson, 1986). The Central Montana Uplift was active in the Early Devonian and other Paleozoic periods (Peterson, 1986). Other important structural features in Montana are Scapegoat-Bannatyne Anticline, Bearpaw Anticline, Yellowstone Park Uplift (Figure 2b). Eastern and central Montana are characterized by less complex structures and more uniform stratigraphy (Peterson, 1986).

Figure 2. (a) The regional extent of the Williston Basin.

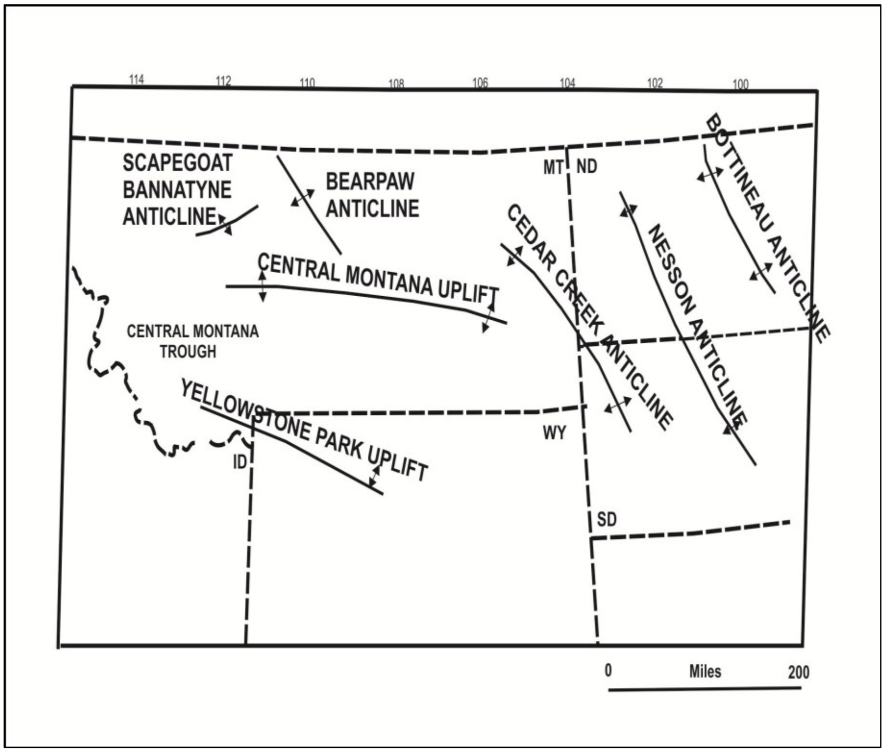

Figure 2. (b) Major structural elements in Montana and adjacent states (Modified from Sandberg and Mapel, 1967; Grader et al., 2011).

2. REGIONAL STRATIGRAPHY

2.1. Three Forks Formation in the Williston Basin and Southern Montana

The Bakken Formation unconformably overlies the Upper Devonian Three Forks Formation (Figure 3a) on the basin flanks of the Williston Basin; however, this contact is conformable in the deeper parts of the basin (Webster, 1984). The Three Forks Formation in the Williston Basin was deposited in shallow marine to supratidal environments in a shallow epeiric sea (Dumonceaux, 1984; Heck et al., 2002) The Three Forks Formation is composed of sandstone, siltstone, shale, anhydrite, and dolomite (Sandberg et al., 1958); its maximum thickness coincides with the basin depocenter.

The Sappington Formation in southern Montana was deposited over the Three Forks Formation above a widespread disconformity (Sandberg, 1965). The Three Forks Formation in western Montana (Figure 3b) is subdivided into two members; the Logan Gulch Member and the overlying Trident Member (Sandberg, 1965).

The earliest Fammennian Logan Gulch Member is 90 to 150 ft (27.4 m to 45.7 m) thick, evaporitic, and non-fossiliferous. It is the most extensive member of the Three Forks Formation and was deposited in an evaporite basin (restricted environment) in northwestern Montana over the Sweetgrass Arch and across into southwestern Montana (Sandberg, 1965). It is equivalent to the upper part of the subsurface Potlatch Anyhdrite of the Three Forks Formation in northwestern Montana (Sandberg and Hammond, 1958; Sandberg, 1965). The basal part of the Logan Gulch Member is mostly silty and dolomitic shale, whereas the upper part is composed of medium gray massive limestone

(Sandberg, 1965; Benson, 1966; Grader et al., 2011). This unit is 111 ft thick (33.8 m; Sandberg, 1965) at the type section at Logan, MT.

The middle Fammenian Trident Member of the Three Forks Formation is composed of highly fossiliferous (brachiopods, bivalves, coral, conularids), argillaceous limestone or calcareous shale that was deposited over a large area under open marine shallow, muddy, but locally restricted conditions in northern and southwestern Montana, southwestern Saskatchewan, and southern and central Alberta (Sandberg, 1963, 1965). The Trident Member is a shallowing-upward unit that includes greenish-gray to yellowish-gray, calcareous, fossiliferous shale at its base and grades upward into marine limestone (Holland, 1952; Sandberg, 1965; Benson, 1966; Grader et al., 2011). The Trident Member is 73 ft (22.3 m) thick at its type section at Logan, MT. A disconformity occurs between the Trident Member of the Three Forks Formation the overlying Sappington Formation (Sandberg, 1965).

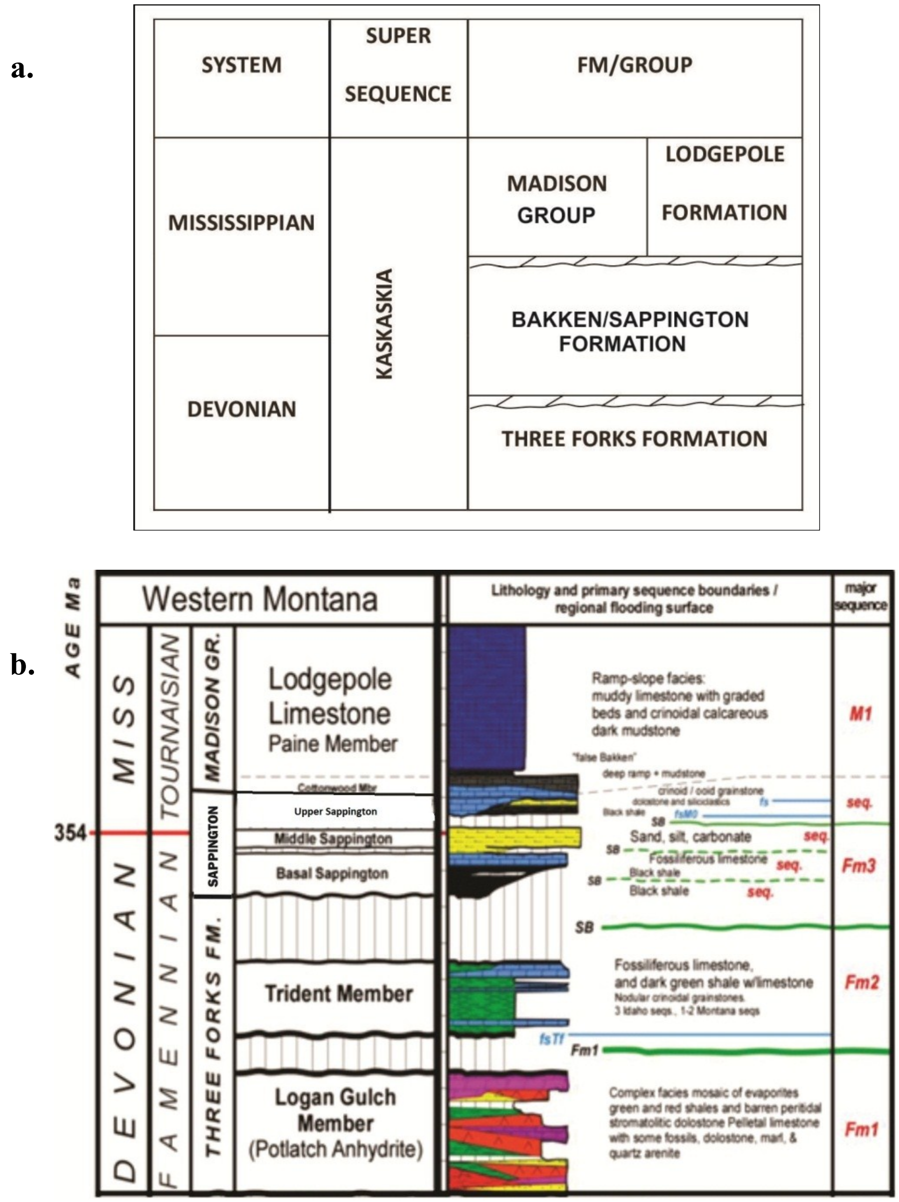

Figure 3. (a) General middle Paleozoic stratigraphy of the Williston Basin (Gerhard et al., 1990; LeFever, 1992). (b) Late Devonian - Early Mississippian stratigraphy of western Montana (Grader et al., 2011).

2.2. Stratigraphy of the Bakken/Sappington Formation in the Williston Basin and Southwestern Montana

The Bakken Formation is divided into 3 informal members in the Williston Basin: the lower, middle and upper members. Lower and upper members are predominantly composed of shale, whereas the middle member includes sandstone, siltstone, dolostone, and limestone (Webster, 1982; Hayes, 1984; Thrasher, 1985). Conodonts from the middle and lower members indicate Late Devonian (Famennian) deposition, whereas upper shale member conodonts indicate Mississippian (Kinderhookian) deposition (Hayes and Holland, 1983).

At the center of the Williston Basin, the lower member of the Bakken Formation has a maximum thickness of 65 ft (20 m), and the thickness of the upper member is as great as 23 ft (7 m; Smith and Bustin, 1996). The shales of the lower and the upper members are hard, siliceous and contain some silica-filled fractures (Webster, 1984). In addition, these units include limited amounts of silt and dolomite grains with local fine-silt sized sphalerite crystals and pyrite-calcite concretions (Webster, 1984; Meissner, 1978). The upper and lower members of the Bakken Formation are organic-rich marine petroleum source rocks with Type 2 kerogen (Dow, 1974; Williams, 1974; Meissner, 1978; Dembicki and Pirkle, 1985; Gerhard et al., 1990) and lesser amounts of herbaceous kerogen and coaly (Type 3) kerogen (Webster, 1984). The upper and lower shales have permeability that ranges from 0.005 to 0.01 milidarcies (Price, 1999). The shale thickness and the total organic content increase towards the basin depocenter, east of Nesson Anticline (LeFever, 1991). The Bakken shales also are continuous reservoirs (self-sourcing) with a widespread consistent lithology (USGS, 2008).

The middle member of the Bakken Formation is lithologically complex with variable thickness. At the Williston Basin center, it conformably overlies the lower shale member. However, along the western basin margin, it unconformably overlies the Three Forks Formation (LeFever, 1991). The middle member is mostly composed of siltstone and sandstone with the lesser amounts of shale, dolostone and oolitic limestone (Webster, 1982; Hayes, 1984; Thrasher, 1985). The middle member consists locally of 5 lithofacies (LeFever 1991; Table 1). Common fossils are brachiopods, gastropods, crinoid pelmatozoans and trace fossils; conodonts, plant spores, and ostrocods are rare (Hayes, 1984).

The middle member of the Bakken Formation is considered to be a tight oil reservoir in the deeper, thermally mature parts of the Williston Basin (Pitman et al., 2001). Permeability of the middle member is generally very low, with an average of 0-20 milidarcies (Pitman et al., 2001). Total porosity (primary and the secondary porosity) of the middle member ranges from 1 to 16%; primary porosity averages 4% (Cox et al., 2008) and is as high as 16% (Pitman et al., 2001). Secondary porosity results from fractures and dolomitization. Average TOC of the middle member is 1%, and Bakken oil is sweet (no H_2S) and light oil (42 degree API; Philips et al., 2007).

Table 1. Middle Bakken Member lithofacies in the Williston Basin (Lefever, 1991).

<table>
<tr><th colspan="2">Lithofacies Name</th><th>Lithology</th><th>Primary Sedimentary Structures</th><th>Other Features and Ichnofacies, and Depositional Environment</th><th>Other Information</th></tr>
<tr><td colspan="2">Lithofacies 5</td><td>Medium to light grey siltstone</td><td>Massive to wispy laminated</td><td>Generally cemented
Slightly bioturbated
Nereites ichnofacies
Offshore
Marine environment</td><td>Sharp contact with upper member</td></tr>
<tr><td colspan="2">Lithofacies 4</td><td>Light to medium grey siltstone, very fine-grained sandstone, medium grey dark grey shale</td><td>Thinly laminated, planar or cross ripple laminations</td><td>Moderately bioturbated, locally cemented vertical burrows, overall coarsening upward Cruiziana ichnofacies.
Lower Shoreface</td><td>Gradational contact with upper member</td></tr>
<tr><td rowspan="3">Lithofacies 3</td><td>Upper</td><td>Light-medium grey argillaceous sandy siltstone, brownish-grey very fine grained sandstone, local claystone</td><td>Wavy to flaser bedded</td><td rowspan="3">Slight to no bioturbation
Skolithos ichnofacies
Tidal Channels</td><td rowspan="3">Most productive unit in North Dakota (9 fields), also in Saskatchewan</td></tr>
<tr><td>Middle</td><td>Fine-medium grained sandstone with medium to dark grey sandstone</td><td>Massive to trough or cross bedded, or thinly laminated</td></tr>
<tr><td>Lower</td><td>Light-medium grey argillaceous sandy siltstone, brownish-grey very fine grained sandstone, local claystone</td><td>Wavy to flaser bedded</td></tr>
<tr><td colspan="2">Lithofacies 2</td><td>consists of greenish-grey to brownish-grey, argillaceous siltstone or sandy siltstone to brownish-grey, very fine grained sandstone</td><td>Small scale clay drapes and burrows, pyrites</td><td>Scattered fossils , crinoids and brachiopods
Offshore
Marine environment</td><td>Productive in Richland County, Montana, North Dakota, lower contact graditional, upper contact graditional or erosive</td></tr>
<tr><td colspan="2">Lithofacies 1</td><td>Calcerous-argillaceous siltstone</td><td>Massive, mottled with calcite cementation</td><td>Pyrite nodules and burrows, intergranuler porosity. Nerites ichnofacies (crinoids, brachiopods)
Offshore
Marine environment</td><td>Graditional or erosive contact with lower member</td></tr>
</table>

The Bakken Formation in the Williston Basin is coeval with the Sappington Formation in southwestern Montana (Nordquist, 1953). Similar to the Bakken, the Sappington Formation is composed of lower and upper shale members with a medial siltstone member. The lower shale member of the Sappington Formation unconformably overlies the Three Forks Formation in southwestern Montana (Figure 4). The unconformity is a sharp erosional surface (McMannis, 1962). The lower shale of the Sappington Formation was deposited upon an erosional surface with very low relief and the Sappington Formation is unconformably overlain by the Lodgepole Formation (Achauer, 1959, Gutschick, 1964). The subsurface units of the each formation in western Montana are indicated in Figure 4.

The Sappington Formation was first named 'Sappington Sandstone' for the upper, yellow, silty-sandy portion of the Three Forks Formation in the Three Forks area of Montana, and Mississippian age was assigned to the unit on the basis of fauna (Syringothyris sp; Berry, 1943). The thin, black shale 35 ft below the Sappington Sandstone was included in the Sappington Formation (Holland, 1952). The Bakken Formation in southern Saskatchewan, southeastern Manitoba and northwestern North Dakota was correlated to the Sappington Formation in northern Montana (Nordquist, 1953). Later, the black shale unit below the crinoidal limestones of the Lodgepole Formation was included to the Sappington Formation (McMannis, 1955). Conodonts indicate that the Bakken Formation in the Williston Basin and the Sappington Formation in southeastern Montana are coeval. The depositional environments (Table 2) of this unit are complex (Gutschick, 1964).

The Sappington Formation (Table 2) is subdivided into six units in southwestern Montana (Gutschick 1964; Grader et al., 2011). Unit 1 represents the lower shale member. Units 2 through 5 are the middle member, and Unit 6 is upper shale member (Figure 5).

Lithology of the lower shale member (Unit 1) varies locally in southwestern Montana, so it is subdivided into subunits A-D (Table 2). The thickness of the lower shale member ranges from 0-43 ft (0-13.1 m) in the study area. The black shale is very thin (approximately 0.5 ft; 0.15 m) at the type section at Logan, MT (Achauer, 1959). Unit D has the widest distribution and it records the strongest marine influence with its diverse fauna (Grader et al., 2011). It is impossible to distinguish Unit 1 from Unit 4 at some locations in the study area, and it can be difficult to separate the lower black shale member from underlying shales of the Trident Member (Grader et al., 2011).

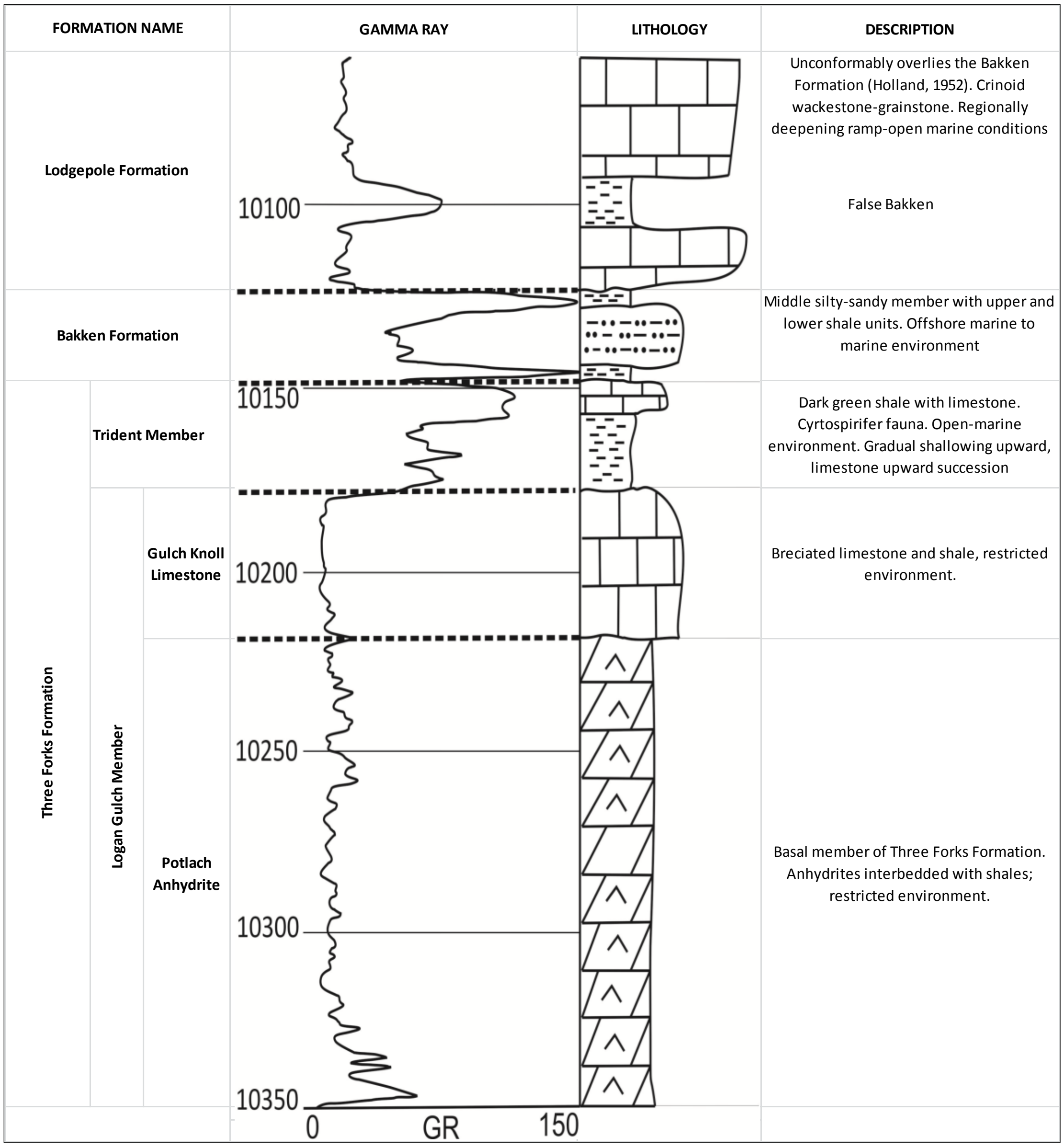

Figure 4. Subsurface units in western Montana (Berry, 1943, 1966; Sandberg and Hammond, 1958, 1965; Gutschick, 1962, Sandberg, 1963).

The Middle Sappington Member is subdivided into 4 units southwestern Montana (Table 2). The lower part of the Middle Sappington Member is composed of burrowed and bioturbated mudstone and siltstone. It grades upward into calcareous limestone with planar and low-angle cross bedding and is capped by hummocky cross stratification. Hence, the Middle Sappington Member shows an overall coarsening-shallowing upward trend indicative of an offshore to shoreface transition (Grader et al., 2011). Units 1 through 6 occur the type section at the Logan, MT, where the middle member is approximately 57 ft (17.4 m) thick, and the lower black shale is 0.5 ft (0.15 m) at the Logan type section, MT (Sandberg, 1965).

The open marine, upper shale member (Unit 6) was eroded or was not deposited at western and southern sections in the Three Forks area (Figure 6). At some locations, the upper black shale member is underlain by yellow, thin-bedded very fine-grained sandstone that is considered to be part of Unit 6, which occurs immediately below the limestone ramp facies of the basal Lodgepole Formation (Figure 6). This sandy unit is reportedly to be both high-energy and low energy unit between the low-energy upper shale member a high-energy Lodgepole Limestone (Grader et al., 2011). It occurs locally where the upper black shale unit is absent, such as at Lone Mountain. Here a sharp contact above the transitional unit separates the Middle Sappington Member from the Lodgepole Formation (Figure 6). All Sappington Members generally have complex lateral facies changes and decrease in thicknesses towards the cratonic high (Central Montana Uplift) to the east (Grader et al., 2011).

Table 2. Units of the Sappington Formation in western Montana (Gutschick 1964; Grader et al., 2011).

Formation Name	Lithofacies Name		Lithology		Fossils and Sed. Str.	Environment
SAPPINGTON FORMATION	Upper Shale Member	Unit 6	Upper dark gray, silty, micaceous, and granular shale (associated with very thin sandstone in eastern CMT)		Conodonts, spores, brachiopods (inarticulate), and fish remains.	Offshore
	Middle Member	Unit 5	Yellow , calcareous, flaggy to massive siltstone and fine sandstone silt-sand		Tubular burrows, arrowheads. Silt-sand bars, mud-silt flats, channel fills, small scale cross str. , ripple marks	Tidal flat-deltaic deposition, oxidizing conditions
		Unit 4	Burrowed, laminated, thin bedded dark shale		burrows (Teichichnus), silt-mud flats, channel fills, ripple marks, sole marking	Mixed marine-brakish water
		Unit 3	Buff-orange lower siltstone		brachiopods, bifungites, crinoids	Transitional (biostrome-mud silt flat)
		Unit 2	Sponge, algal, buff silty limestone		crinoids, bryzoans (algae-sponge bistrome)	Shallow water marine
	Lower Shale Member	Unit 1	D	light olive-gray, granular and noncalcareous shale	brachiopods, clams, snails, and crinoid stems	Restricted marine to deep marine
			C	brownish-gray to brownish-black, thin, compact, fissile shale	most fossiliferous bed with Conchostracans, inarticulate brachiopods, starfish, and plant spores.	
			B	Dark gray, glossy, contorted, carbonaceous shale	plant spores	
			A	dark, marine, well laminated, not fissile	few plant spores,conodonts	

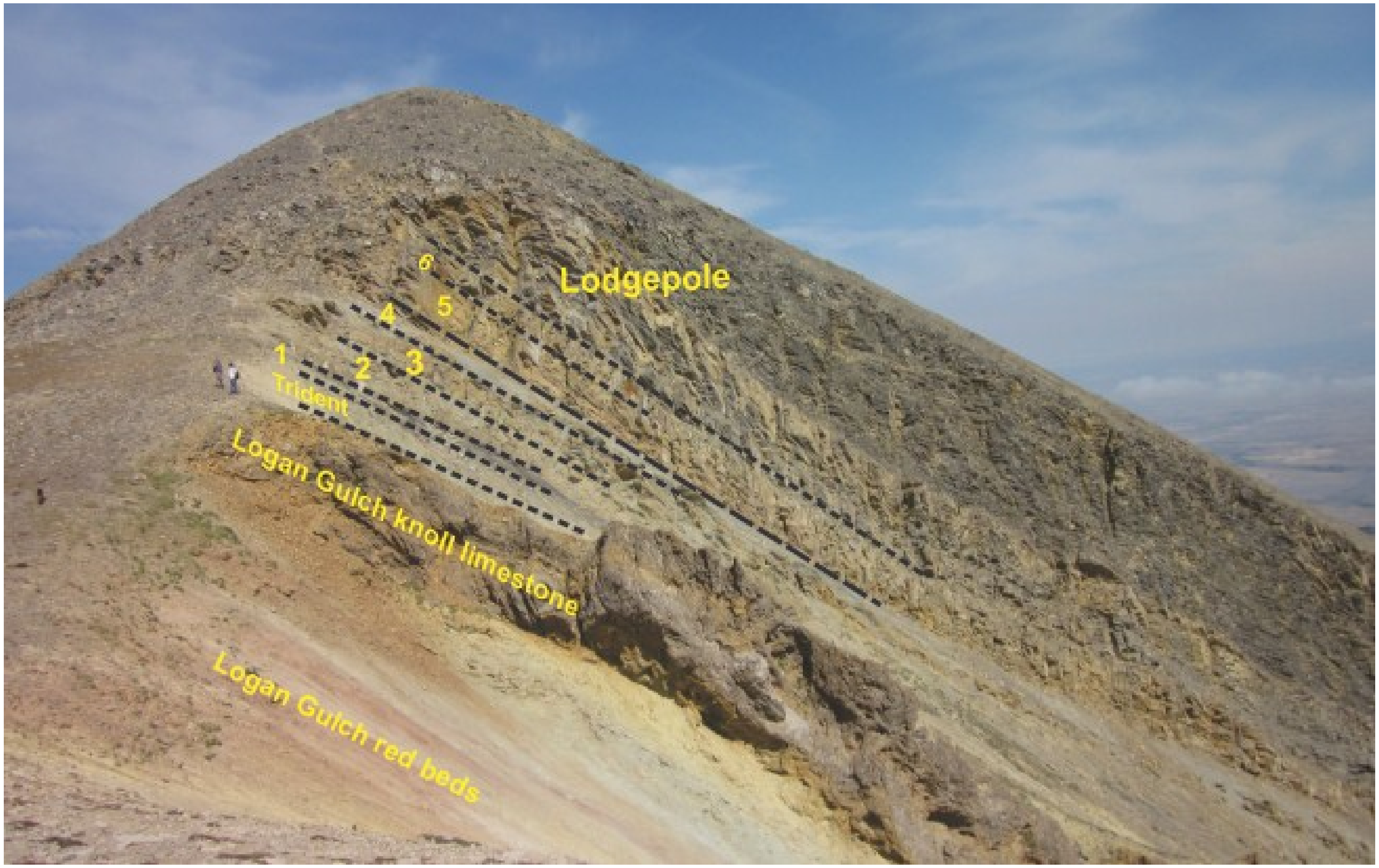

Figure 5. Outcrop of the Sappington, Three Forks and Lodgepole Formations at Hardscrabble Peak (Modified from Grader et al., 2011).

a b

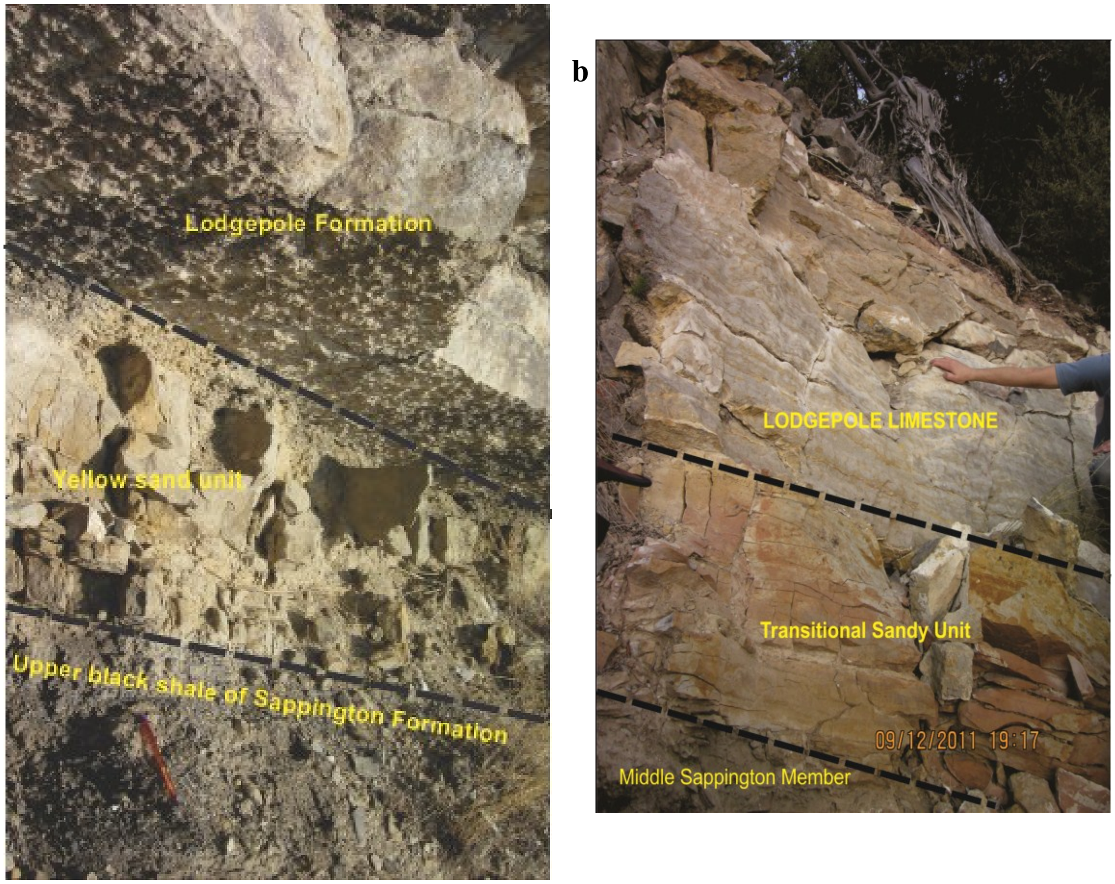

Figure 6. (a)Yellow sandy transitional unit with the upper black shale and the Lodgepole Formation at Logan Devonian type section. (b) Contacts between Middle Sappington, transitional sandy unit and the Lodgepole Limestone at Lone Mountain.

3. STRATIGRAPHIC CORRELATION OF THE BAKKEN/SAPPINGTON FORMATION IN MONTANA

3.1. Outcrop-to-Log Correlation

Gamma-ray logs of outcrops in southwestern Montana (Milligan Canyon, Beaver Creek, Logan Gulch, and Hardscrabble-Fairy Lake Cirque) were generated with a hand-held scintillometer (Grader et al., 2011) to tie with subsurface data and to determine the lateral changes of the Sappington Formation units in the Three Forks study area. The south-north cross section (Figure 7) covers the outcrops of Milligan Canyon and Beaver Creek, and the well logs of Cascade, Teton and Pondera Counties. The east-west cross section (Figure 8) includes the outcrops of Milligan Canyon, Logan Gulch, and Hardscrabble Peak with the subsurface data of southern Montana.

The transgressive lower shale member of the Sappington Formation is composed of dark brown and calcareous mudstone at Milligan Canyon and it has high gamma ray values. The basal shale overlies a sequence boundary above the Trident Member of the Three Forks Formation at Milligan Canyon. The lower shale member has high gamma ray values. The Middle Sappington Member is a shallowing upward unit at Milligan Canyon with overall decreasing (or cleaning)-upward gamma-ray response. The upper shale member is absent at Milligan Canyon; instead, a synsedimentary folded crinoid-bearing transitional sandstone unit (Unit 6?) is located below the Lodgepole Formation. In northwestern Montana, all Sappington Members are present, further northwest, the total thickness of the Sappington Formation decreases in the subsurface, only a thin (7 ft; 2.1 m thick) lower shale member of the Sappington Formation remains (Figure 7).

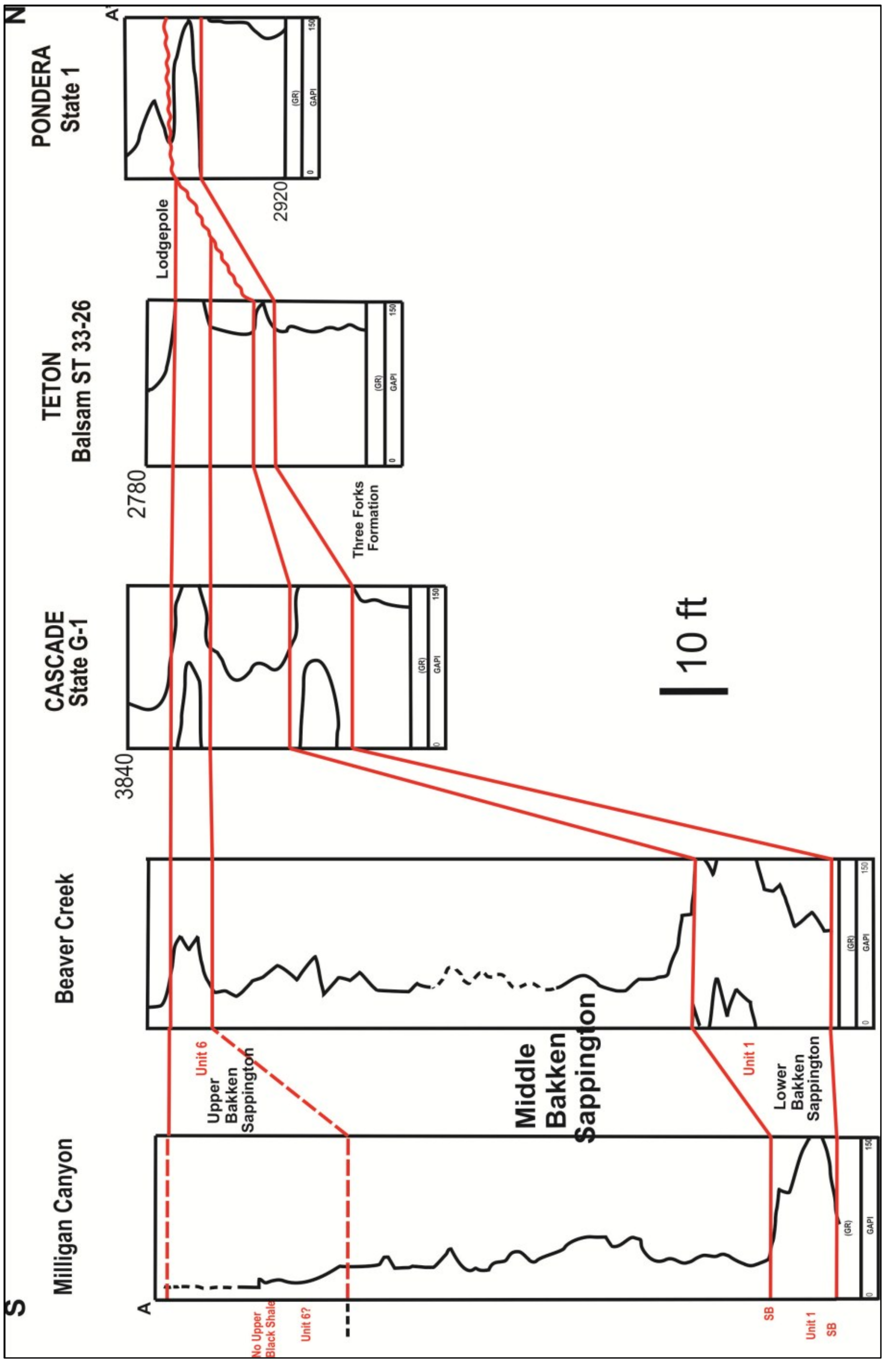

Figure 7. South-north outcrop to subsurface correlation in western Montana (no horizontal scale, see Figure 1 for location).

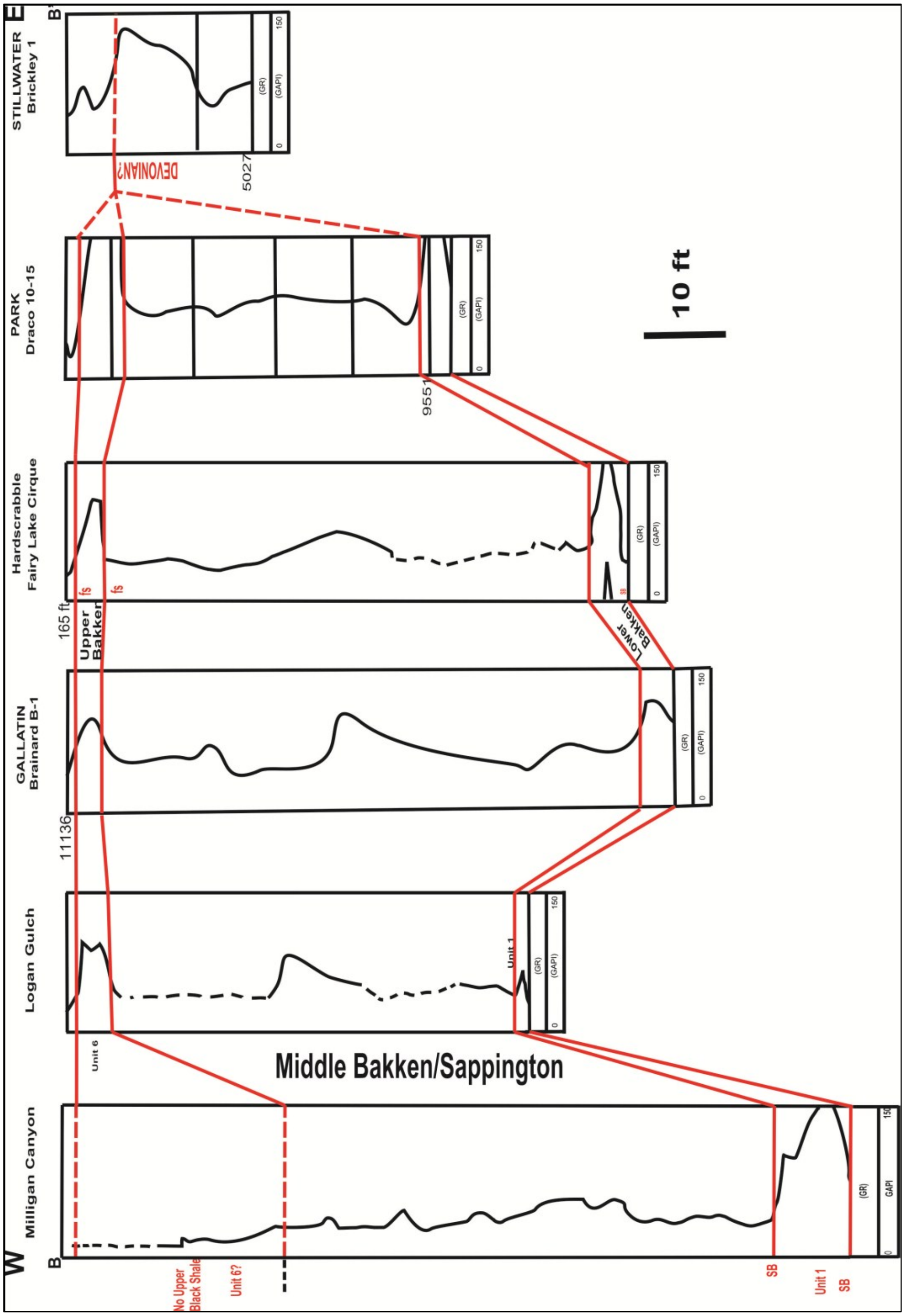

Figure 8. West-east outcrop to subsurface correlation in western Montana (no horizontal scale, see Figure 1 for location).

The west-east correlation (Figure 8) starts at Milligan Canyon outcrop, where the upper black shale is absent. However, the Upper Sappington Member occurs at the Logan Gulch and Hardscrabble Peak outcrop. The overall thickness in the Bakken/Sappington Formation decreases eastward from Milligan Canyon and the Devonian units cannot be differentiated in well logs in central and south central Montana.

3.2. Core-to-Log Correlation

Five cores (Figure 1 and Table 3), in the United States Geological Survey (USGS) Core Research Facility in Denver, Colorado, were described with the handlens and binocular microscope. Only two cores, 1 Big Sky HD (from Roosevelt County) and 1-4 Williams (from Richland County) had available wireline logs. Cores were described bed-by-bed by characterizing lithology, fossil content, sedimentary structures, and grain size distributions. Dunham's classification (1962) was used for carbonate rocks, and the Wentworth scale was used for siliciclastic rocks.

Table 3. List of the Bakken Formation cores (see Figure 1 for locations).

Well Name	Core Interval	Township	Range	Section	County
1 Big Sky HD	9,875-9,930	30N	58E	2	Roosevelt
1-4 Williams	10,047-10,081	23N	55E	4	Richland
44-24 Vaira	9,986-10,049	24N	54E	24	Richland
A-1 Stark	9,181-9,235	10N	60E	15	Fallon
5H Joyes State	6,768-7,778	37N	57E	16	Sheridan

The five cores have similar facies (Table 4). The cores commonly begin in the Three Forks Formation and continue through the Lower, Middle and Upper Bakken Members. Briefly, the Lower and the Upper Bakken Members are black shale and the Middle Bakken Member is lithologically complex, being composed of siltstone, dolostone and muddy siltstone. The Middle Bakken Member includes basal transgressive lag deposits composed of subrounded quartz grains, pyrite, and fossil fragments (Alexandre et al., 2011). The lithofacies of the middle member is modified from Alexandre et al., 2011 and it is subdivided into A, B, C, D, E and F units. However some lithological description for each unit might show differences in this study. Lithofacies A is clay rich siltstone-dolostone with fossil brachiopods and crinoids (Alexandre et al., 2011). Lithofacies B is highly bioturbated silty dolostone (siltstone for this study) with little or no current features and the clay content generally decreases upward (Almanza, 2011; Alexandre et al., 2011). Lithofacies C is very fine-grained silty dolostone (siltstone or muddy siltstone for this study) with planar, subparallel, wavy, and small-scale cross-laminations with bioturbation. Lithofacies D is very thin sandy interval that genearally cannot be differentiated or it is included to Lithofacies C. Lithofacies E is silty dolostone (siltstone for this study) with fair to moderate bioturbation and some current and tidal features (Almanza, 2011; Alexandre et al., 2011). Lithofacies F is silty fosilliferous dolostone (siltstone for this study) is bioturbated, and its clay content increases upward (Alexandre et al., 2011; Almanza, 2011).

Table 4. Description of the available Bakken cores.

Well Name	Lithofacies Name		Rock Type	Structural Features and Fossil Content	Depositional Environment
1 Big Sky HD	Upper Bakken		Black Shale	Parallel Laminations	Offshore Marine
	Middle Bakken	F	Muddy Siltstone	Helmintophsis	Offshore Subtidal Marine
		E	Siltstone	Hummocky Cross Beddings, Parallel Laminations, Bioturbation	Lower Intertidal
		C	Siltstone	Parallel, Wavy, Irregular Laminations, Bioturbation	Upper Shoreface
		B	Siltstone	Bioturbation, Helmintophsis, Brachiopods	Lower Shoreface
		A	Dolomite	Massive	Offshore Marine
	Lower Bakken		Black Shale	Parallel Laminations	Offshore Marine
1-4 Williams	Upper Bakken		Black Shale	Parallel Laminations	Offshore Marine
	Middle Bakken	C	Siltstone	Trough Ripples	Intertidal
		B	Siltstone	Bioturbation, Brachiopods, Helmintophsis, Nereites	Lower Shoreface
		A	Siltstone	Bioturbation, Brachiopods	Offshore Marine
Vaira 44-24	Upper Bakken		Black Shale	Parallel Laminations	Offshore Marine
	Middle Bakken	C	Muddy Siltstone	Trough Ripples, parallel Laminations, Bioturbation, Brachiopods, Helmintophsis, Nereites	Intertidal
		B	Muddy Siltstone	Bioturbation, Brachiopods, Helmintophsis, Nereites	Lower Shoreface
		A	Muddy Siltstone	Brachiopods	Offshore Marine

Table 4. Continued

Well Name	Lithofacies Name		Rock Type	Structural Features and Fossil Content	Depositional Environment
A-1 Stark	Middle Bakken	B	Siltstone	Mud Stringer, Bioturbation	Lower Shoreface
		A	Dolomite	Parallel Laminations	Offshore Marine
5H Joyes State	Middle Bakken	F	Muddy Siltstone	Bioturbation	Offshore Subtidal Marine
		E	Muddy Siltstone	Bioturbation, Parallel Laminations, Mud Stringer, Trough Ripples	Lower Intertidal
		C	Siltstone	Trough Ripples, Wavy, Irregular Laminations,	Upper Shoreface
		B	Muddy Siltstone	Bioturbation, Wavy, Parallel Laminations, Mud Stringers	Lower Shoreface

The cored interval of Big Sky 1 well (Figure 9) in Roosevelt County is 9,875-9,930 ft (3,010- 3027 m) (with 50 ft; 15.2 m recovery), and it includes all three members of the Bakken Formation (Table 4). The lowest 5 ft (1.5 m) of core is the uppermost Three Forks Formation, which is light to dark gray, fossiliferous siltstone that is intensely bioturbated near the base. The lower black shale of the Bakken Formation was deposited unconformably on the Three Forks Formation. The lag deposits occur between the Three Forks and the Bakken Formation. A sharp unconformity occurs between the lower black shale and the Middle Bakken Member that is represented by Lithofacies A, B, C, E, and F. The upper black shale member unconformably overlies the middle siltstone member and its lithology is same to the lower black shale member. When the core data of the 1 Big Sky well are tied to the log data (Figure 10), it is clear that the core does not have the complete upper black shale interval; approximately 5 ft (1.5 m) is not cored. The lower and the upper shale members have very high GR values, whereas the middle siltstone member is cleaner with lower GR values.

The 1-4 Williams core in Richland County (Figure 11) is approximately 34 ft (10.4 m) thick (10,047-10,072 ft; 3,062.3-3,069.9 m). The Three Forks Formation is in the base of the core and it is overlain by transgressive lag deposits, and the gray, Medial Bakken Siltstone Member that is composed of Lithofacies A, B and C (Almanza, 2011) (Table 4). There is unconformity between the Three Forks Formation and the Middle Bakken Member and between the Middle Bakken and the Upper Bakken Member. When the core data are tied to the wireline logs (Figure 12), it is clear that the shaly interval with high GR values does not represent the Lower Bakken Member, since it is missing on the core data. The Bakken Formation starts with middle siltstone member. The middle siltstone member has cleaner GR values than the upper black shale member and GR log shows thickening/cleaning-upward log trend for the middle member. The upper black shale member was not cored in the 1-4 Williams well. According to the wireline log data, the upper shale member continues approximately 7 ft (2.1 m) above the cored interval in the Williams well.

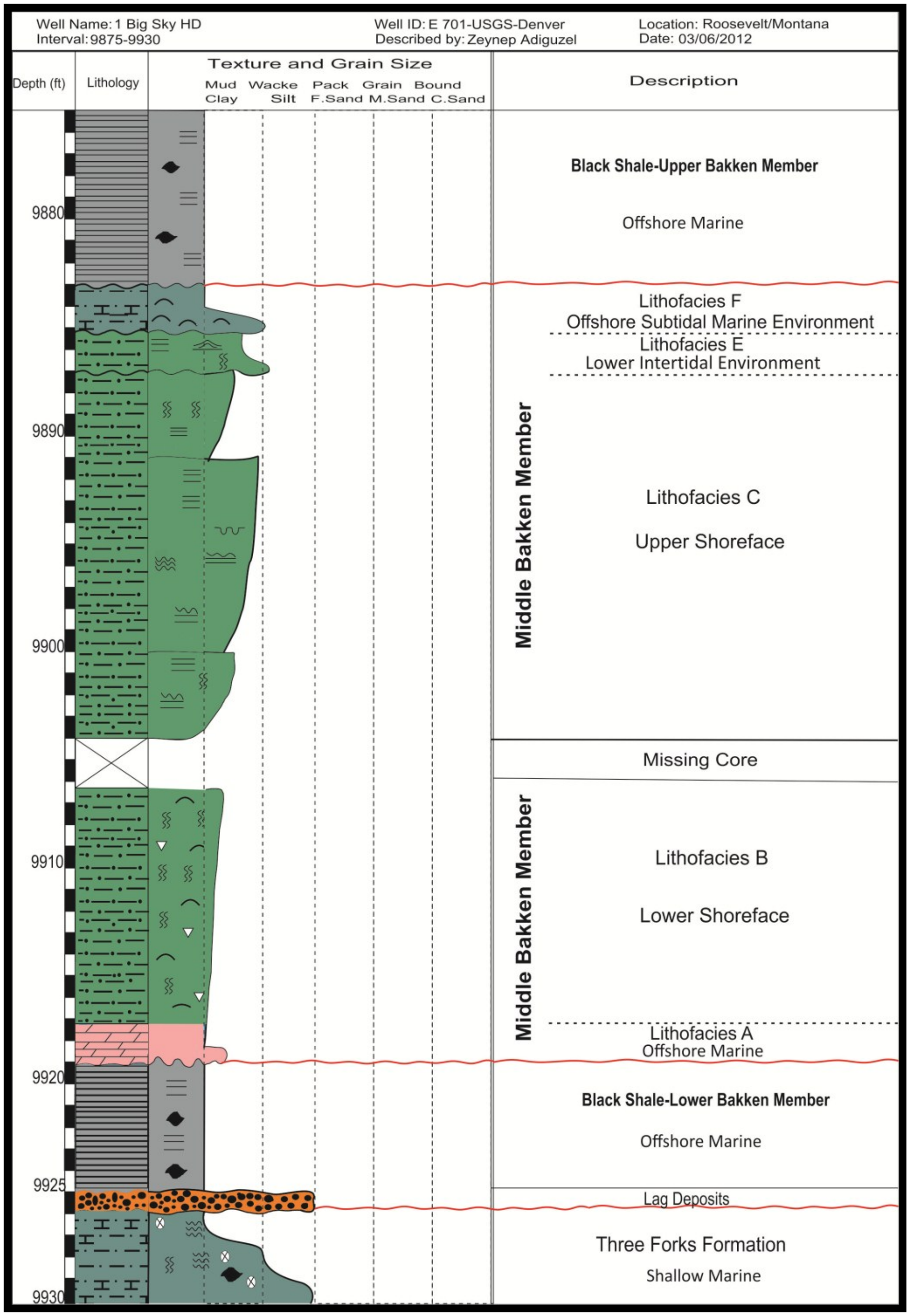

Figure 9. 1 Big Sky HD well core description (see Figure 1 for well location and Appendix B for symbols).

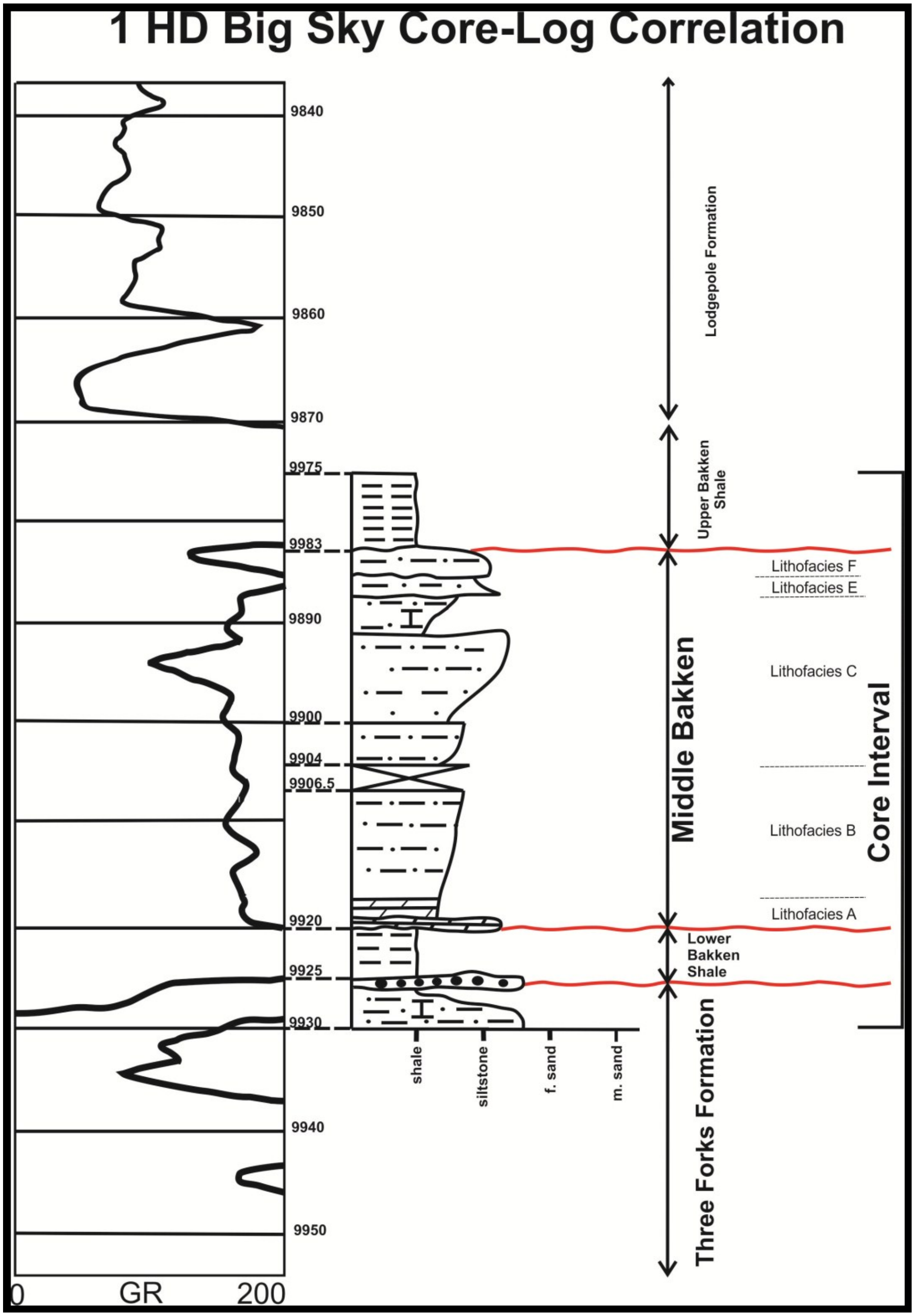

Figure 10. 1 HD Big Sky well core-subsurface correlation (see Figure 1 for well location and Appendix B for symbols).

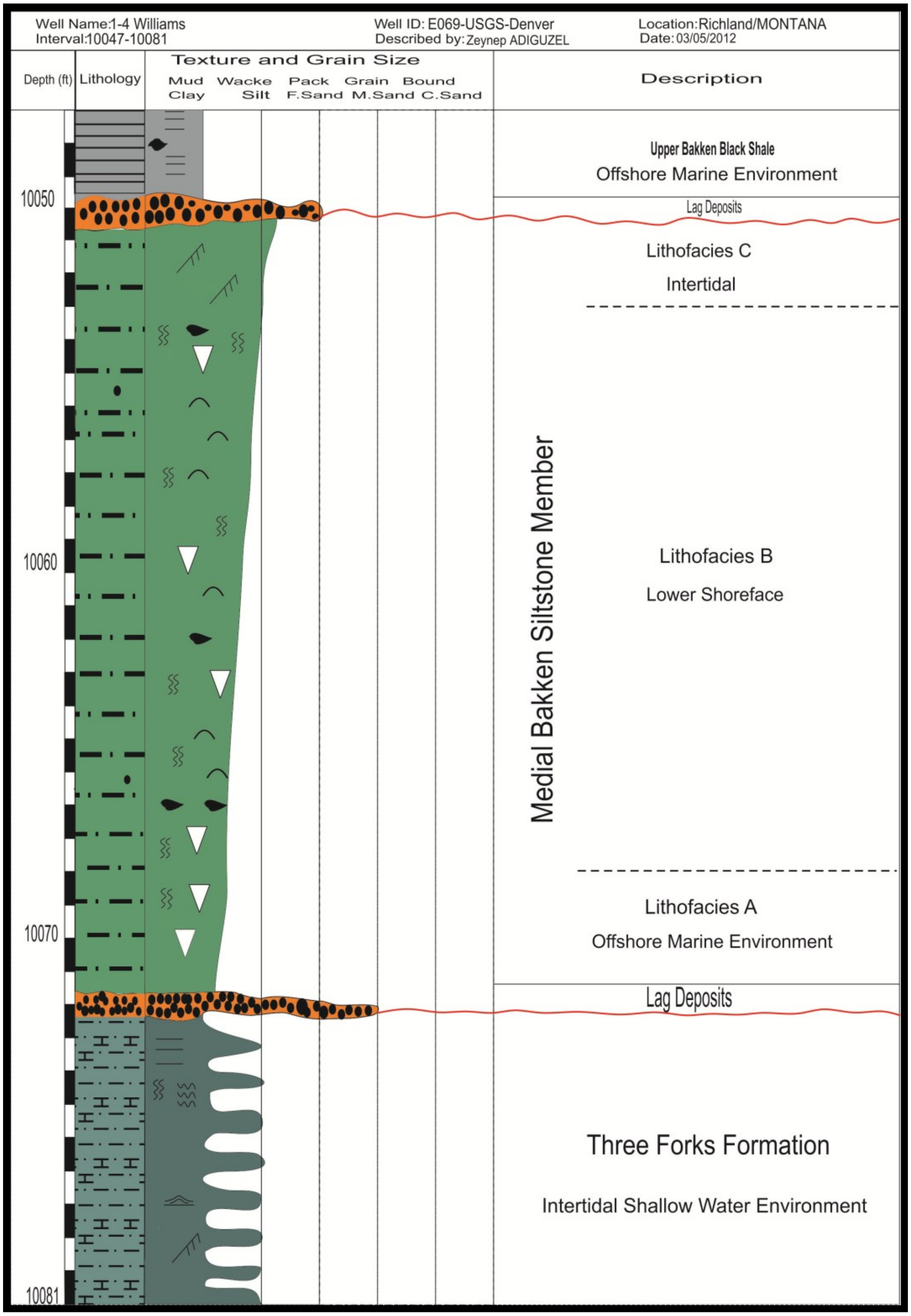

Figure 11. 1-4 Williams well core description (see Figure 1 for well location and Appendix B for symbols).

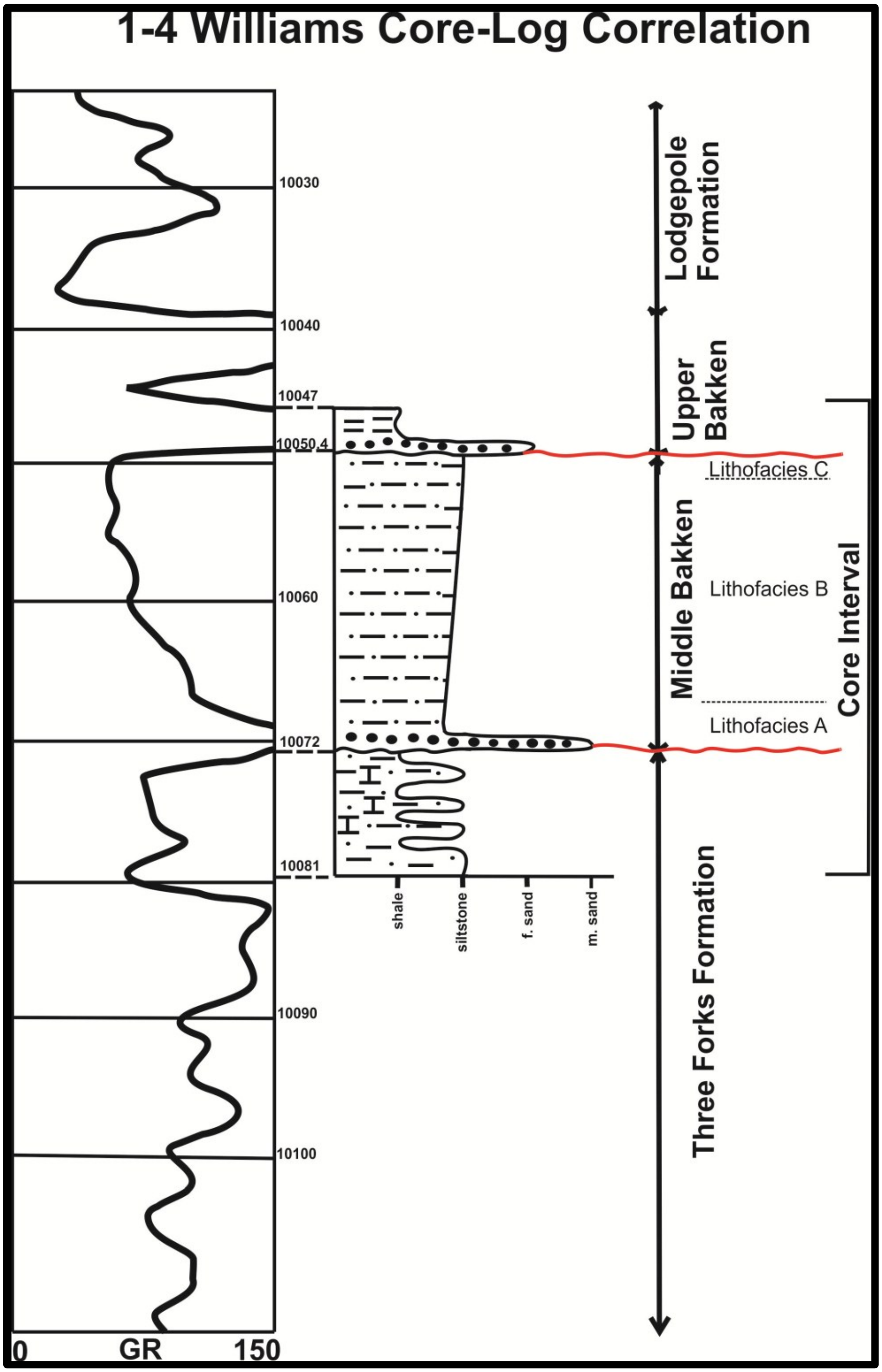

Figure 12. 1-4 Williams well core-subsurface correlation (see Figure 1 for well location and Appendix B for symbols).

The cored interval of the Vaira 44-24 well (Figure 13 and Table 4) in Richland County is 9,986-10,045 ft (3,043.7- 3,061.7 m). The contact is sharp between the Bakken Formation and the Three Forks Formation. The contacts between the Bakken Members are also sharp. Middle Bakken is composed of three Lithofacies: A, B, and C (Almanza, 2011). The unconformably overlying Lodgepole Formation includes a fossiliferous black shale unit, called the 'False Bakken'.

The A-1 Stark well in Fallon County (Figure 14, and Table 4) is 54 ft (16.5 m) thick (9,181-9,235 ft; 2,798.4-2,814.8 m core interval), and the Lower Bakken Member does not occur here; the contact between the Middle Bakken Member and the Three Forks Formation is unconformable. The Middle Bakken Member is Lithofacies A and B. The Upper Bakken Shale sharply overlies the Middle Bakken Member.

The cored interval of 5H Joyes State well in Sheridan County (Figure 15, Table 4) includes only the Middle Bakken Member; the lower and the upper black shale member were not cored. The middle member is composed of Lithofacies B, C, E, and F.

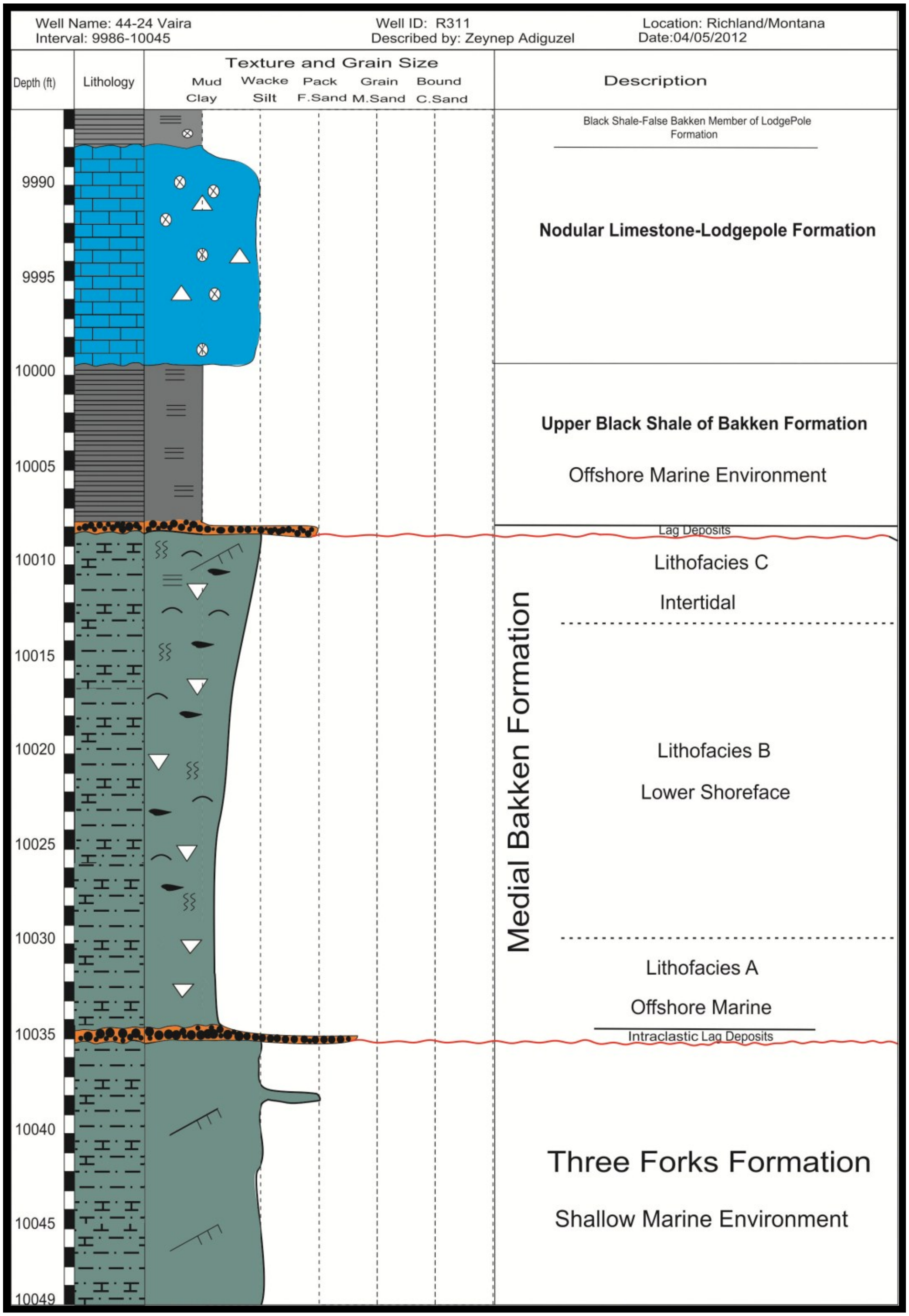

Figure 13. 44-24 Vaira well core description (see Figure 1 for well location and Appendix B for symbols).

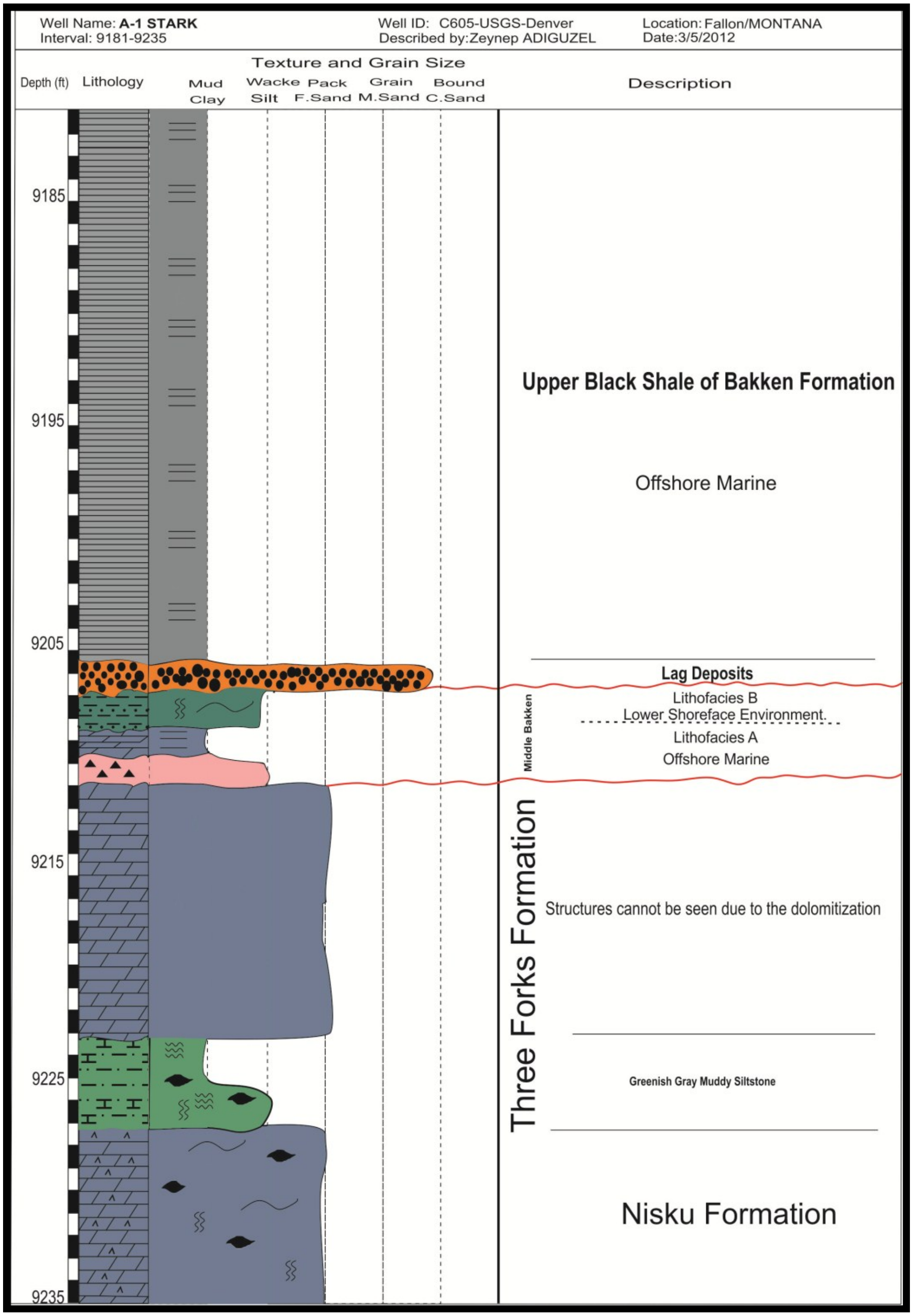

Figure 14. A-1 Stark well core description (See Figure 1 for well location and Appendix B for symbols).

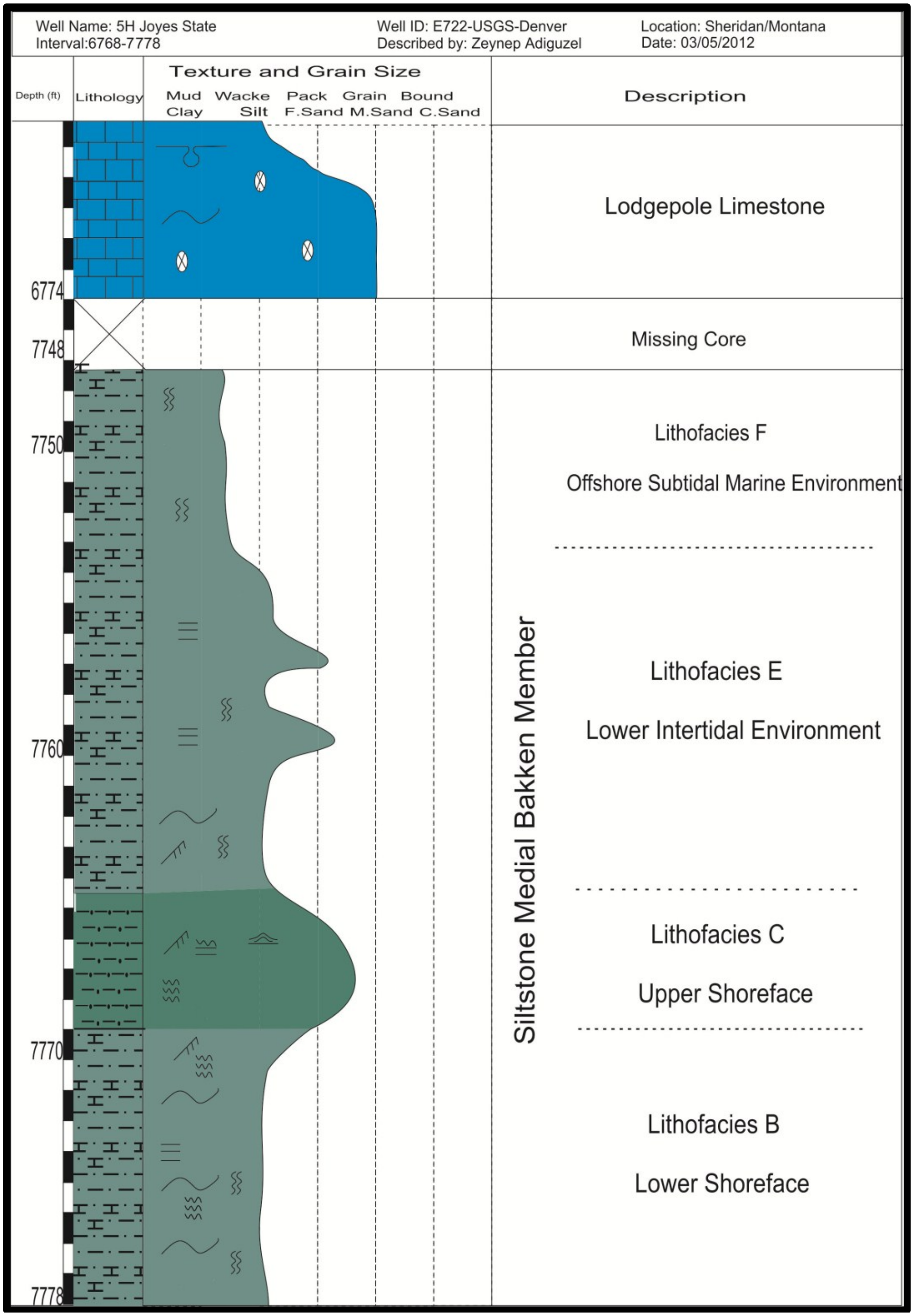

Figure 15. 5H Joyes State well core description (See Figure 1 for well location and Appendix B for symbols).

3.3. Log-to-Log Correlation

The main focus of this study was the subsurface correlation of the Bakken/Sappington Formations across Montana. Several N-S and E-W cross sections (Figure 16-22) clarify lateral relationships of these strata.

Although the Bakken Formation in the Williston Basin is relatively thin, it has a unique well-log pattern (Webster, 1984). The lower and upper members are shale units that are easily recognized on wireline logs by their high (greater than 200 API) gamma ray values (Webster, 1984; LeFever, 1991). The lower and the upper members of the Bakken Formation in the Williston Basin may have low or high resistivity values. The low resistivity readings (less than 10 ohmmeters) occur where the Bakken Formation is not thermally mature and the shale has conductive water in its pores (Webster, 1984; Meissner, 1978). The depth for the low resistivity readings are generally less than 6,500 ft (1,981 m; Meissner, 1978). In the deeper parts of the basin, at depths greater than 7,000-8,000 ft (2,130-2,440 m), the Bakken is thermally mature and has higher resistivity (greater than 100 ohmmeters), owing to hydrocarbon saturation (Meissner, 1978, Webster, 1982). Hydrocarbon saturation resulted from replacement of highly conductive pore water in the shales with nonconductive hydrocarbons (Meissner, 1978). The middle member of the Bakken Formation has relatively clean (<150 API) gamma ray values representing the well-cemented carbonates and siliciclastics (Webster, 1984).

The wireline logs in the Montana part of the Williston Basin record presence of all three Bakken Members. The upper and the lower shale members are good markers to distinguish the Bakken Formation from the overlying Lodgepole Formation and the underlying Three Forks Formation. However, if there is no lower black shale, it is hard to distinguish the middle member of the Bakken Formation (or equivalent Sappington Formation) from the underlying Three Forks Formation in the Williston Basin and in southwestern Montana, because the lithology of these units is similar.

In southwestern Montana, the basal shale unit of the Sappington Formation is generally black or brown, and the Trident Member of the underlying Three Forks Formation is mostly green, highly fossiliferous, argillaceous lime mudstone-calcareous shale at outcrops (Sandberg, 1963, 1965). However, it is impossible to see these color changes and/or the fossil content in the subsurface data, so differentiating of the Lower Bakken Member from the Trident Member of the Three Forks Formation in southwestern and northwestern Montana is challenging. Also, the unconformity between the Trident Member of the Three Forks Formation and the Lower Sappington Member (McMannis, 1962) can be used as a marker at outcrops but not in well logs. However, the Bakken Formation cores are mostly from eastern Montana. In this study, the Lower Bakken Member was differentiated from the Trident Member and the lower member of the Bakken/Sappington Formation on the basis of gamma ray values in western Montana. The Lower Sappington Member is picked where the gamma ray values are high (>100 API) and, 'relatively' lower gamma ray values (<100 API) occur in the Trident Member of the Three Forks Formation. Neutron logs of the Lower Bakken Member have anomalously high neutron porosity values in southwestern and northwestern Montana, and in the Williston Basin. Similarly density porosity values in the Bakken/Sappington Formation are much higher than the underlying Trident Member of the Three Forks Formation.

The basal member of the Three Forks Formation is the Logan Gulch Member which is sub-divided into two informal members in the subsurface: the basal Potlatch Anhydrite and the upper Gulch Knoll Limestone (Perry, 1928; Wilson, 1955, Grader et al., 2011). The top of the Gulch Knoll Limestone is identified mostly based on the gamma ray logs because it is 'cleaner' (lower gamma ray value) than the overlying Trident Member. The Gulch Knoll Limestone is generally thin in western Montana and does not occur in the Williston Basin. The Potlatch Anhydrite is a massive anhydrite unit interbedded with dolomite. The Potlatch Anhydrite is picked on the density-neutron logs since the anhydrite has very low neutron porosity and density porosity values.

The Lower Mississippian Lodgepole Formation is commonly easily differentiated from the Bakken/Sappington Formation on the wireline logs where the Upper Bakken/Sappington Member occurs, because the lower Lodgepole has a very clean gamma ray response. However, where the Lodgepole Formation includes a 'False Bakken' which has similar features to the Upper Bakken/Sappington Shale Member, it can be difficult to differentiate the "False Bakken' of the Lodgepole Formation from the 'upper shale member' of the Bakken Formation. In general the neutron porosity values of the Upper Bakken Member are higher than those of the False Bakken, and the resistivity values of the False Bakken are not as high as those of the Upper Bakken/Sappington Member.

The Trident Member of the Three Forks Formation below the Sappington Formation in southwestern Montana ranges from 13 ft to 55 ft thick (4 m-16.7 m), in southwestern Montana and its thickness increases towards northwestern Montana (Figure 16). The Gulch Knoll Member of the Three Forks Formation also is widespread across the northwestern-southwestern Montana. The Potlatch Anhydrite is the thickest Three Forks unit in the subsurface attains a maximum thickness (approximately 70 ft; 21.3 m) near Pondera, Montana (Figure 16). The Sappington Formation is well developed in southwestern Montana; all three members are present and total thickness is approximately 80 ft (24.4 m) thick (Figures 16, and 24). Towards northwestern Montana, overall thickness of the Bakken/Sappington Formation decreases and only a thin (~6 ft; 1.8 m), shaly interval occurs in northwestern Montana (Figures 16, 24, and 25).

The Bakken/Sappington Formation extends from northwestern to northeastern Montana (Figure 17). Towards northeastern Montana, thin Lower Bakken/Sappington Shale Member (~ 6 ft; 1.8 m) disappears, and an interval with cleaner gamma ray values is the only unit (Figure 17). This interval is thought to be the middle member (~20 ft; 6.1 m) of the Bakken/Sappington Formation, since it is located immediately below the Lodgepole Formation, and the unit below the Bakken/Sappington has the well log characteristics of the Trident Member of the Three Forks Formation. The members of the Three Forks Formation are not distinguishable in northeastern Montana (Figure 17). The Montana portion of the Williston Basin generally has the three members of the Bakken Formation and the thicknesses of these members increase towards North Dakota

(Figures 17, 24). The thickness of the Bakken Formation ranges from 50-95 ft (12-28.9 m) in the northeastern Montana, and it occurs approximately 7,000-10,000 ft (2,136.6-3,048 m) below the surface.

In northeastern Montana, the three members of the Bakken/Sappington Formation (Figures 18, 24) have total thickness ranging from 50-90 ft (15.2-27.4 m). However, along the basin flanks, the formation thins, and the middle and the lower members terminate (Figure 18). In Fallon and Prairie Counties, the Bakken is generally absent or is very thin (~8 ft and ~6 ft respectively; 2.4-1.8 m) at around 8,500 ft (2,591 m) depth. The units below the Upper Bakken Member mostly cannot be differentiated in Fallon and Prairie County. The thickness of the Bakken Formation in Richland County is approximately 40 ft (12.2 m) and the formation depth is approximately 10,300 ft (3,139 m) (Figure 18).

The west-east cross section (Figure 19) from northwestern Montana continues to the Williston Basin to the east. The seven ft (2.1 m) thick Lower Bakken/Sappington Shale in Lewis and Clark County thickens eastward to approximately 25 ft (7.6 m) in Cascade County and then it thins further to the east. In Garfield and Fergus Counties, the Bakken/Sappington is very thin (~4 ft; 1.2 m) or non-existent. The Sappington Formation is ~7 ft (2.1 m) thick in Petroleum County where it is composed of just one shaly interval. The intervals below the Bakken/Sappington shale unit cannot be differentiated along the Central Montana Uplift. The thickness of the Bakken/Sappington Formation increases toward the Williston Basin to the east.

The southernmost cross section (Figure 20) shows a thick Bakken/Sappington Formation in southwestern Montana (80 ft; 24.4 m thick). However, towards southeastern Montana, the Devonian units cannot be differentiated; so, the base of the Lodgepole Formation is picked as the Devonian top.

The westernmost south cross section (Figure 21) shows the Bakken/Sappington Formation approximately 50 ft (15.2 m.) thick in the southwestern Montana, towards north, its thickness decreases. The south-north cross section (Figure 22) in the central part of Montana indicates that the Bakken/Sappington Formation in south central Montana is absent. However, towards northern Montana, the Bakken/Sappington Formation, mostly the middle member, is about 30 ft (9.1 m) thick.

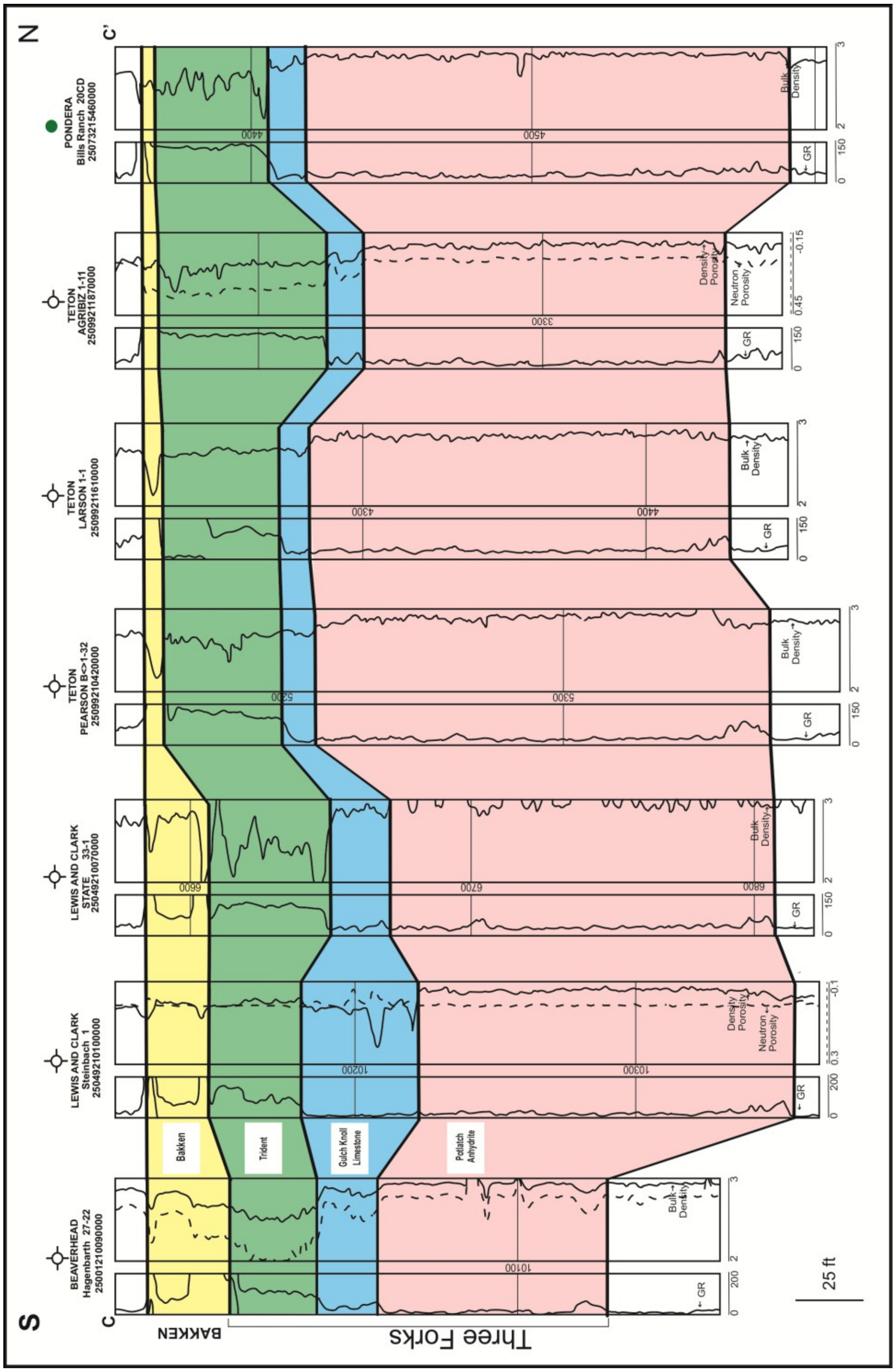

Figure 16. S-N stratigraphic cross section C-C' (datum is the Bakken/Sappington Formation top, see Figure 1 for location).

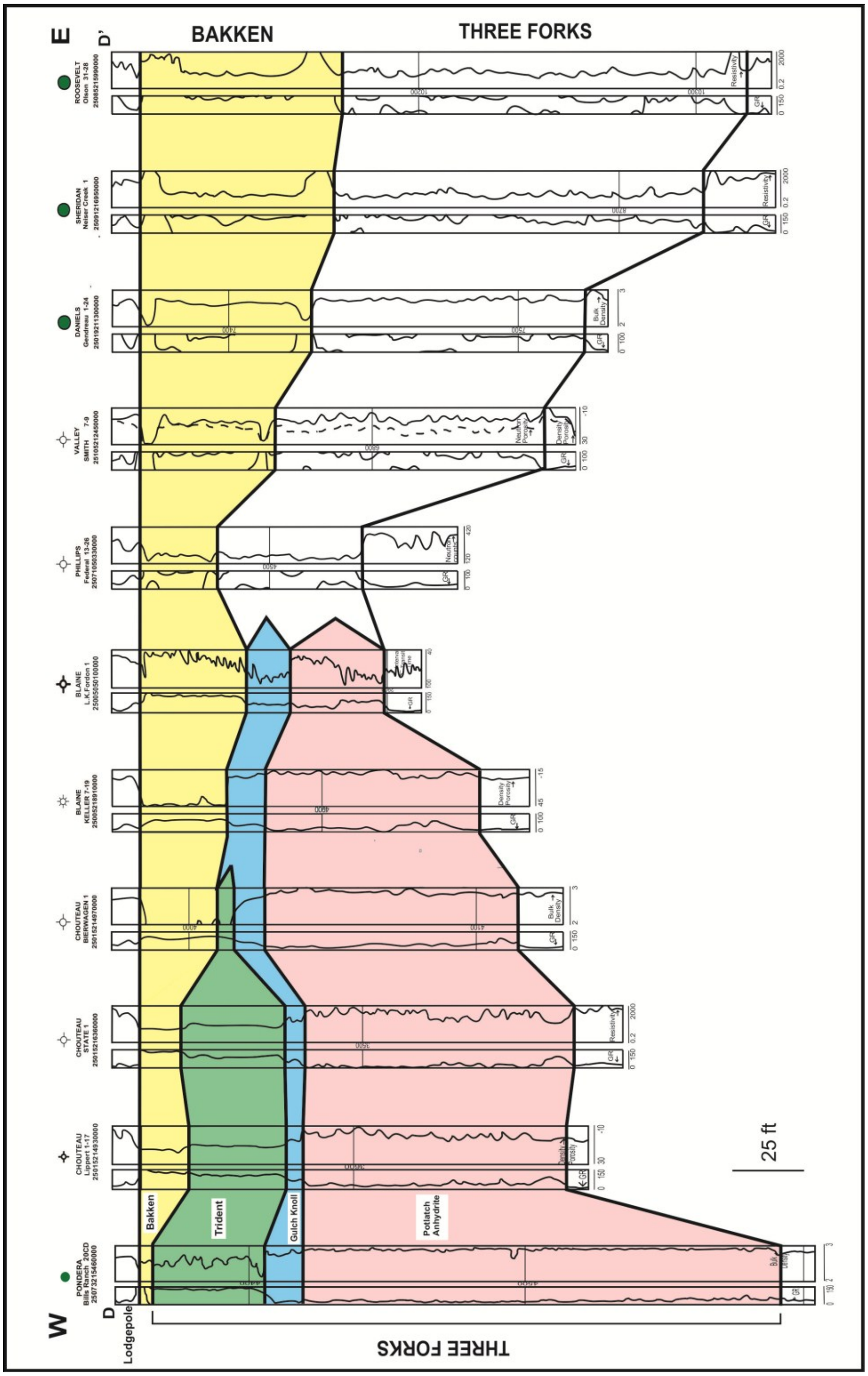

Figure 17. NW-NE stratigraphic cross section D-D' (datum is the Bakken/Sappington Formation top, see Figure 1 for location).

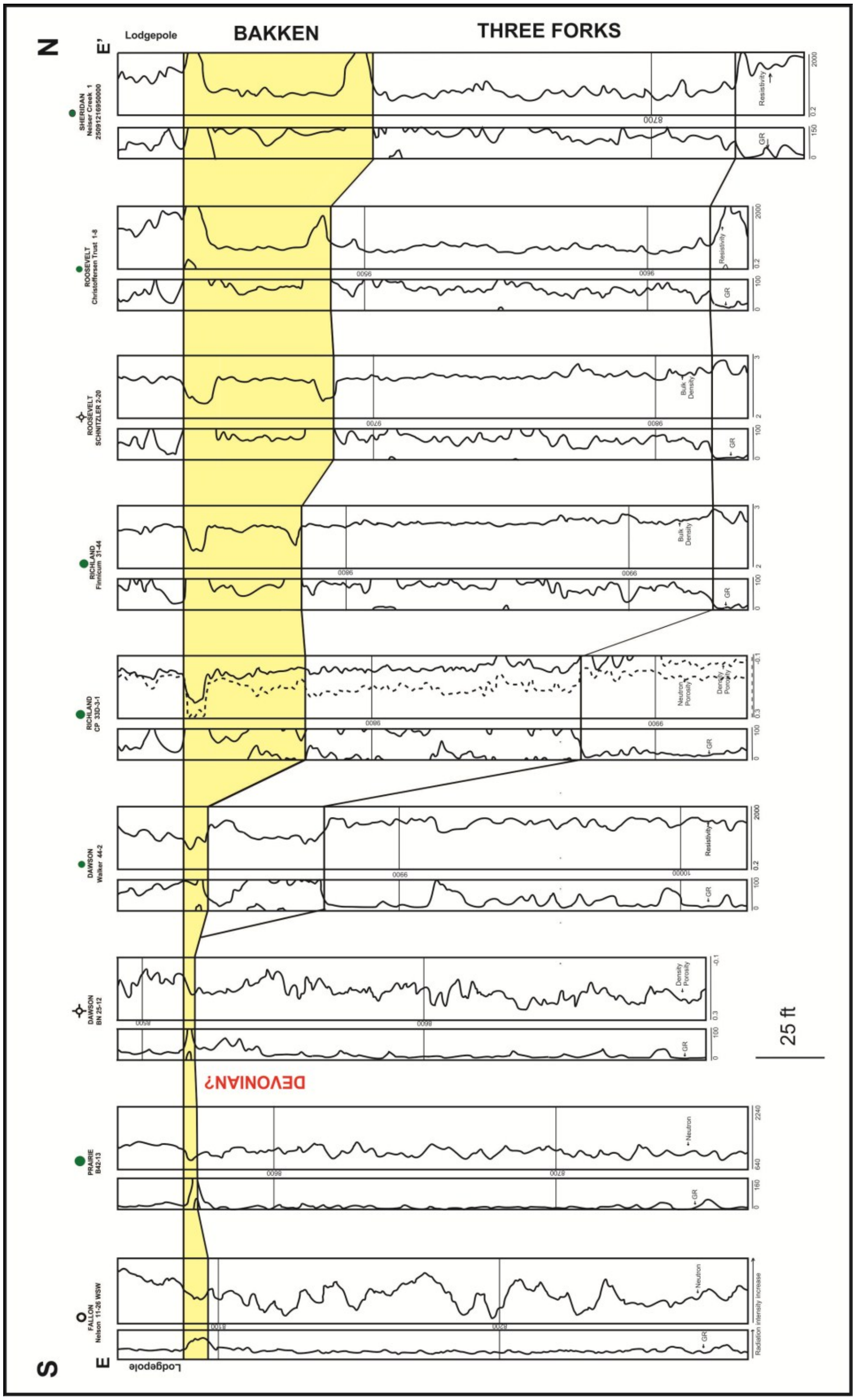

Figure 18. S-N stratigraphic cross section E-E' (datum is the Bakken/Sappington Formation top, see Figure 1 for location).

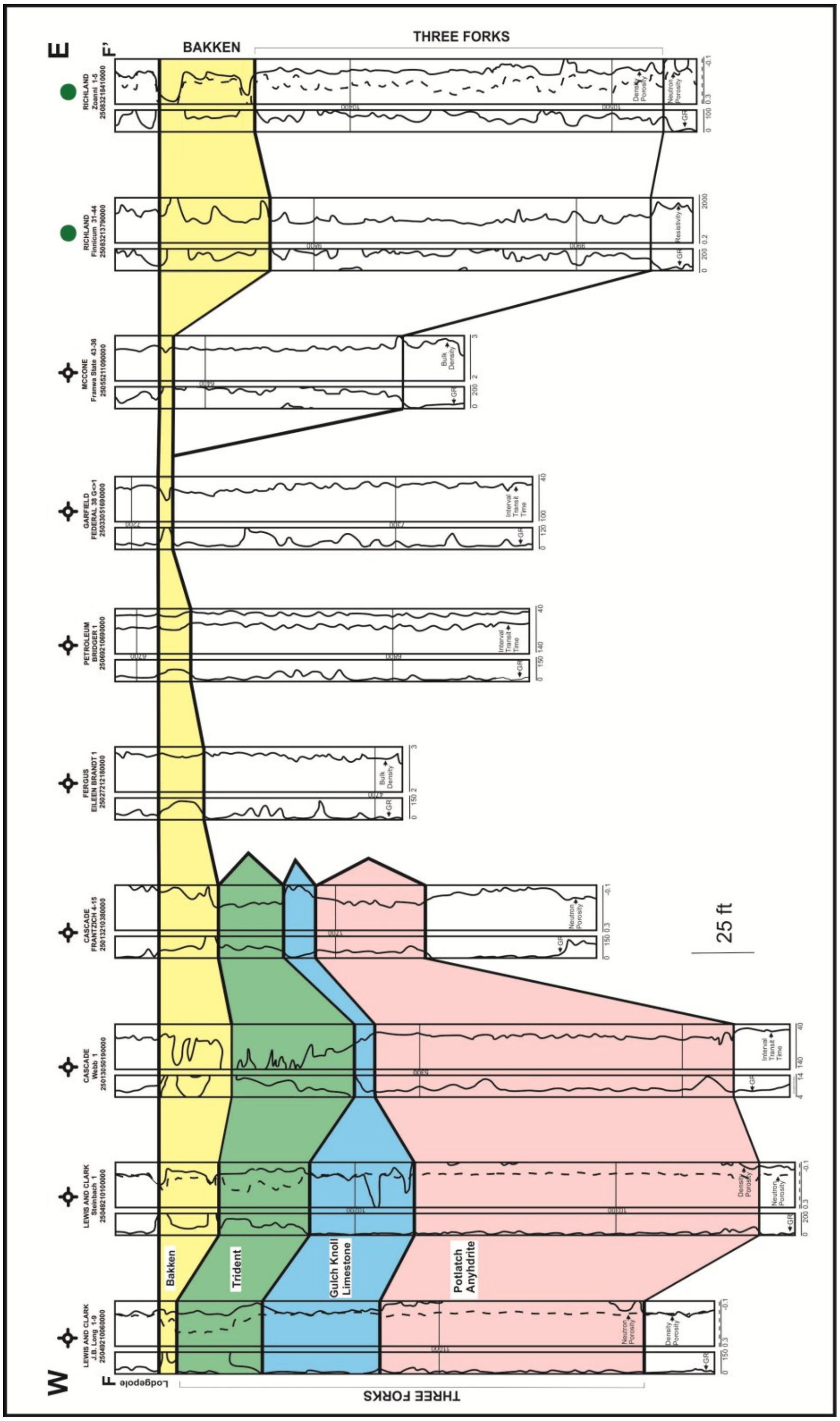

Figure 19. W-E stratigraphic cross section F-F' (datum is the Bakken/Sappington Formation top, see Figure 1 for location).

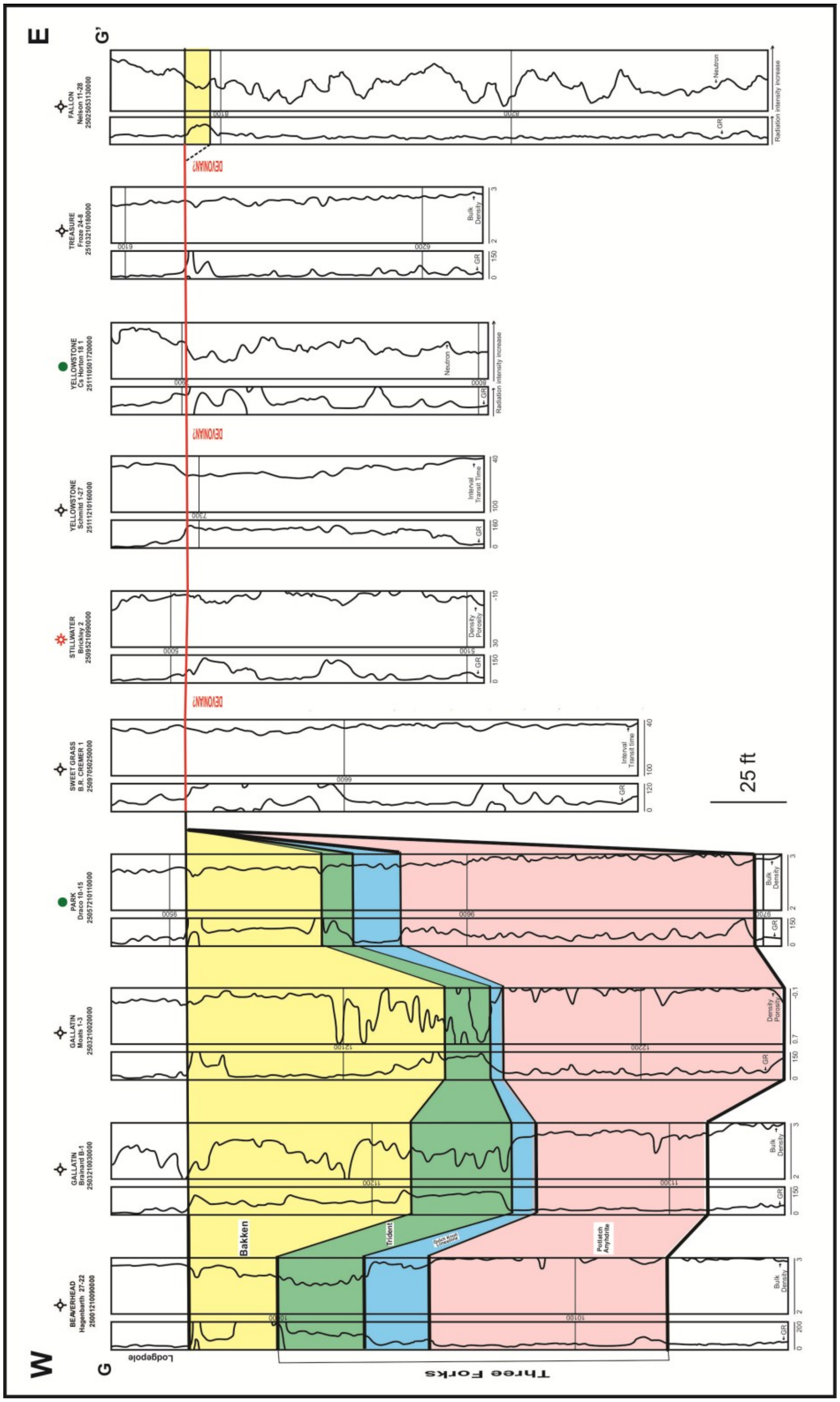

Figure 20. W-E stratigraphic cross section G-G' (datum is the Bakken/Sappington Formation top, see Figure 1 for location).

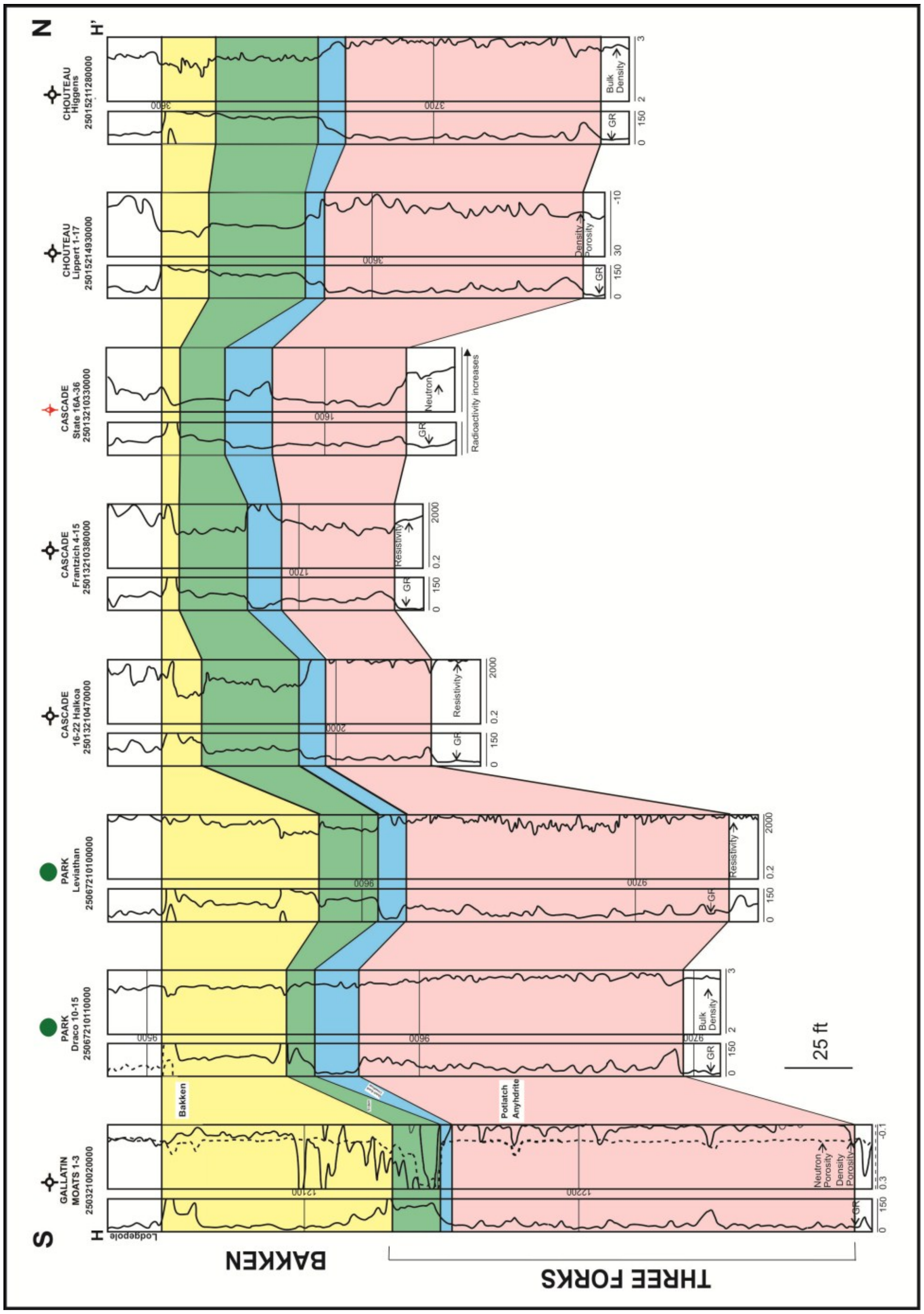

Figure 21. S-N stratigraphic cross section H-H' (datum is the Bakken/Sappington Formation top, see Figure 1 for location).

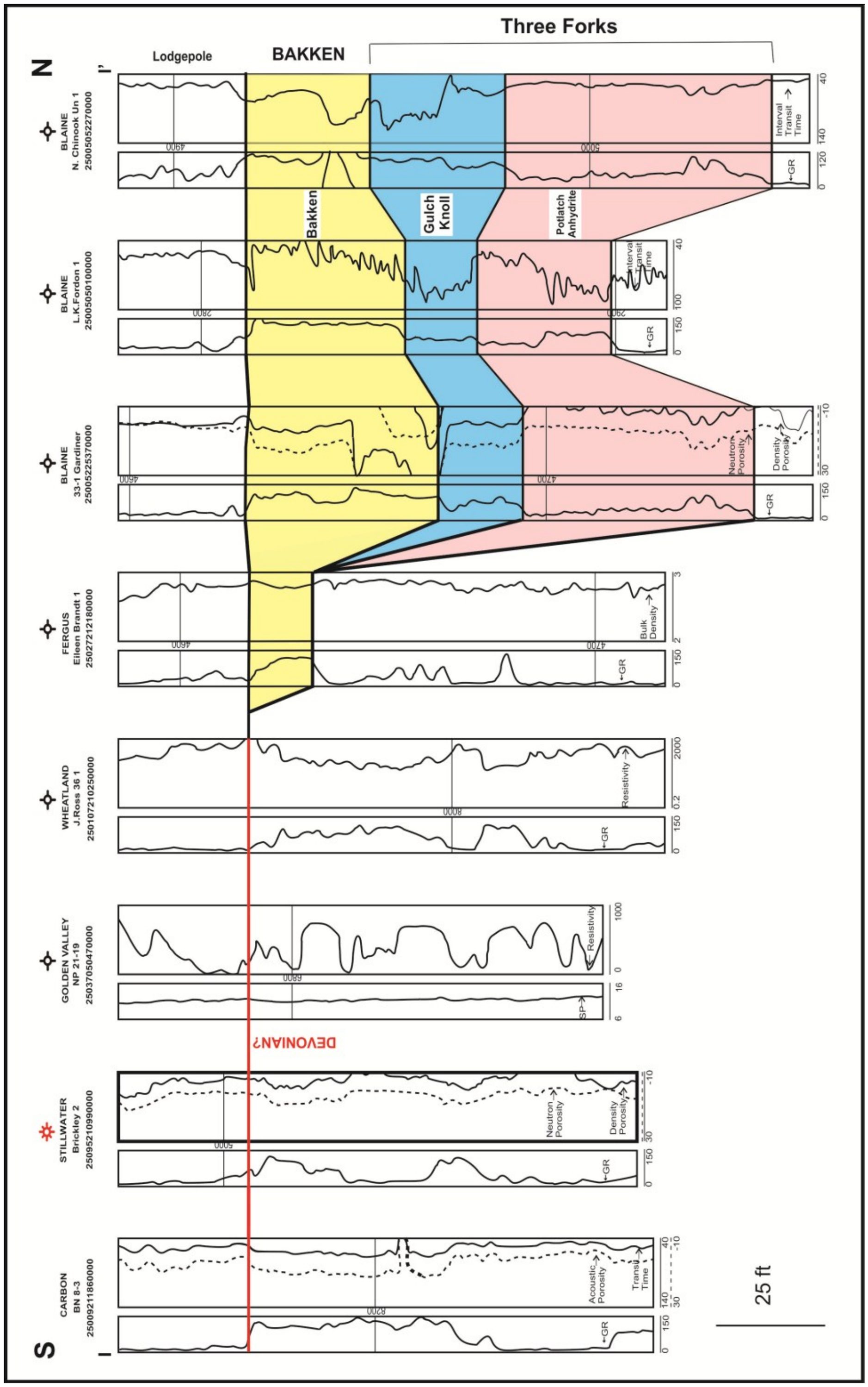

Figure 22. S-N stratigraphic cross section I-I' (datum is the Bakken/Sappington Formation top, see Figure 1 for location).

3.4. Structure Assessment

The structural top (Figure 23) of the Bakken/Sappington Formation was mapped using data from 420 wireline logs. The relief of the Bakken/Sappington top is approximately 7,000 ft (2,133 m). Several uplifts and depressions occur in Montana. The uplifts are represented by the shallow elevations (0 to -2,000 ft; 0-610 m) and the deepest parts ranging from -5,000 ft to -9,000 ft (1,524-2,743 m) subsurface level indicating the depressions. The Scapegoat-Bannatyne Anticline is located in northwestern Montana, and the Bearpaw Anticline is in the north-central part of the state. Other uplifts in central Montana and southern Montana are the Central Montana Uplift and Yellowstone Park Uplift, respectively (Figure 23). Depressions on the map record basins (Figure 23). The depression in southwestern Montana is the Central Montana Trough, and the basin in northeastern Montana is the western flank of the Williston Basin in Montana.

3.5 Thickness and Extent of the Bakken/Sappington Formation

Four isopach maps were made to evaluate the lateral thickness changes and extent of the Bakken/Sappington Formation and its members in Montana. One isopach map (Figure 24) shows the total thickness of the Bakken/Sappington Formation in Montana and the other three maps (Figures 25, 26, and 27) show the distribution of the Lower, Middle and Upper Bakken/Sappington Members across Montana.

The total Bakken/Sappington Formation isopach map is based on approximately 420 wells (Figure 24). The Bakken/Sappington Formation is thickest in two areas in Montana (Figure 24); one is located in southwestern Montana and other is in the northeastern corner of Montana. In southwestern Montana the Bakken/Sappington Formation is up to 80 ft (24.4 m) thick. However, towards the east, thickness of the formation decreases (Figure 24). From southwestern to northwestern Montana, the formation thickness decreases from ~80 ft (24.4 m) to ~6 ft (1.8 m). The Bakken/Sappington Formation thickens from northwestern Montana to the Williston Basin, where its maximum exceeds 90 ft (27.4 m).

Isopach maps of Bakken/Sappington Members were made using data from 261 wells in Montana (Figures 25-27). All three members of the Bakken Formation are thickest in the northeastern and the southwestern corners of Montana (Figures 25-27). The thickness of the Lower Bakken/Sappington Member exceeds 15 ft (4.6 m) in southwestern Montana, and it thins to 6 ft (1.8 m) in northwestern Montana (Figure 25). The thickness of the Middle (~60 ft; 18.3 m) and the Upper Bakken/Sappington (greater than 10 ft; 3 m) Members in southwestern Montana decreases to northwestern Montana and both units are absent in far northwestern Montana (Figures 26 and 27).

The Lower and the Upper Bakken/Sappington Members occur on the northwestern flank of the Williston Basin, where they are more than 10 ft (3 m) but their thickness decrease towards the west and the south (Figures 25, and 27). The thickness of the Middle Bakken Member in the Williston Basin ranges from 0 on the basin flanks to 65 ft (19.8 m) at the northwestern corner of the Williston Basin (Figure 26). The thickness of the Upper Bakken Member is as great as 13 ft (3.9 m) in Sheridan and Roosevelt Counties, and its thickness decreases south and west of the Williston Basin (Figure 27).

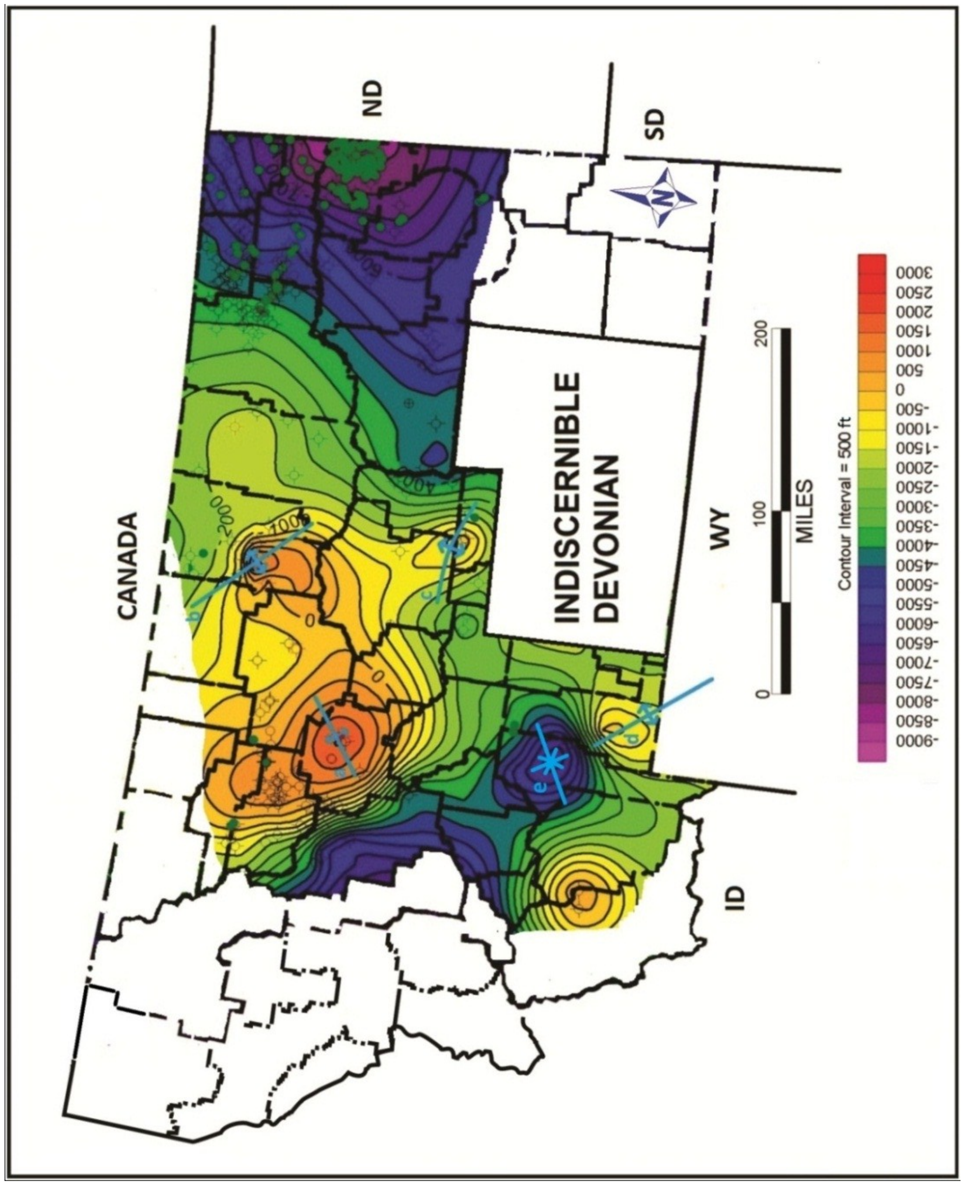

Figure 23. The structural map of the top of the Bakken/Sappington Formation a. Scapegoat-Bannatyne Anticline, b. Bearpaw Anticline, c. Central Montana Uplift, d. Yellowstone Park Anticline, e. Central Montana Trough.

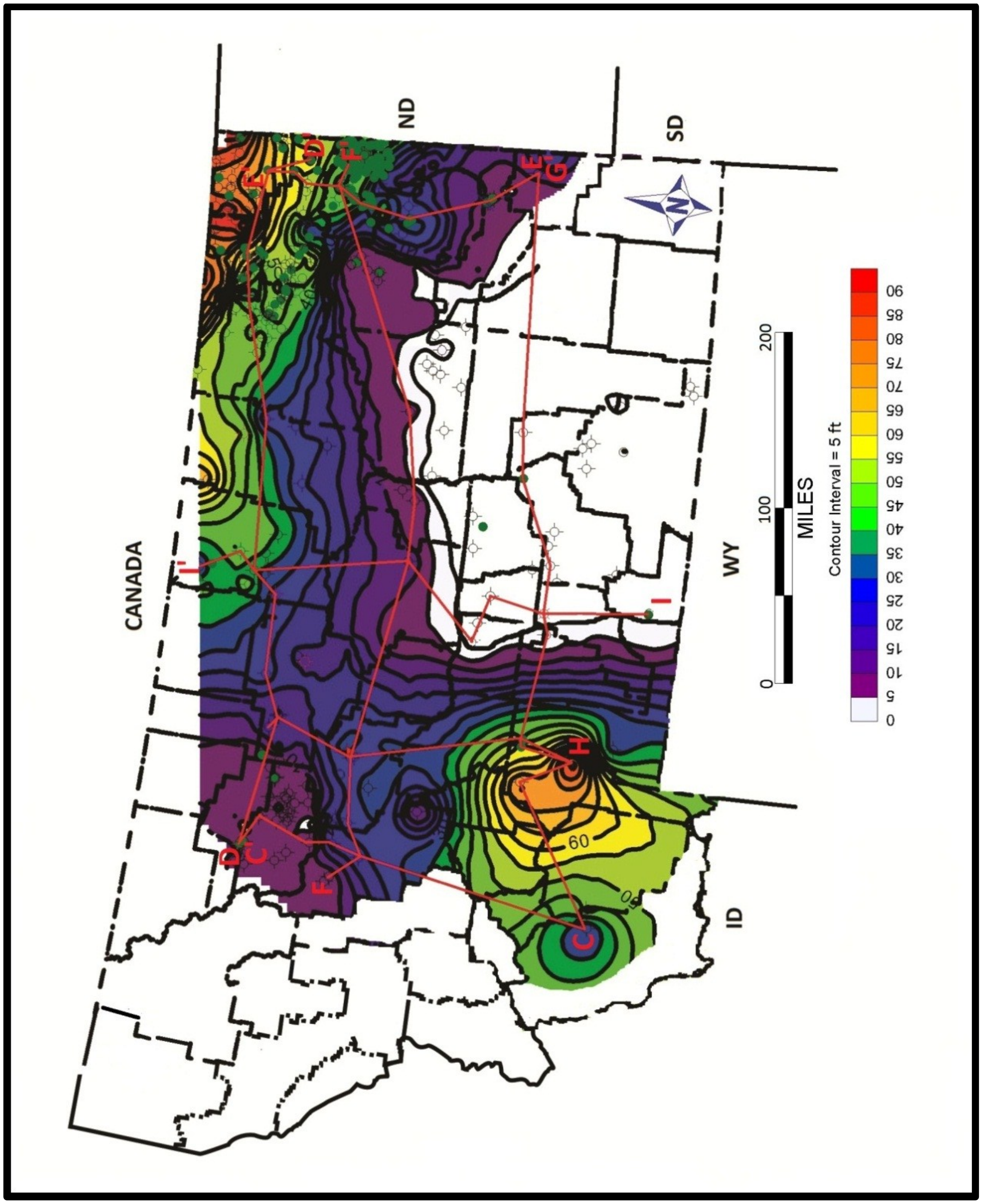

Figure 24. Total thickness of the Bakken/Sappington Formation.

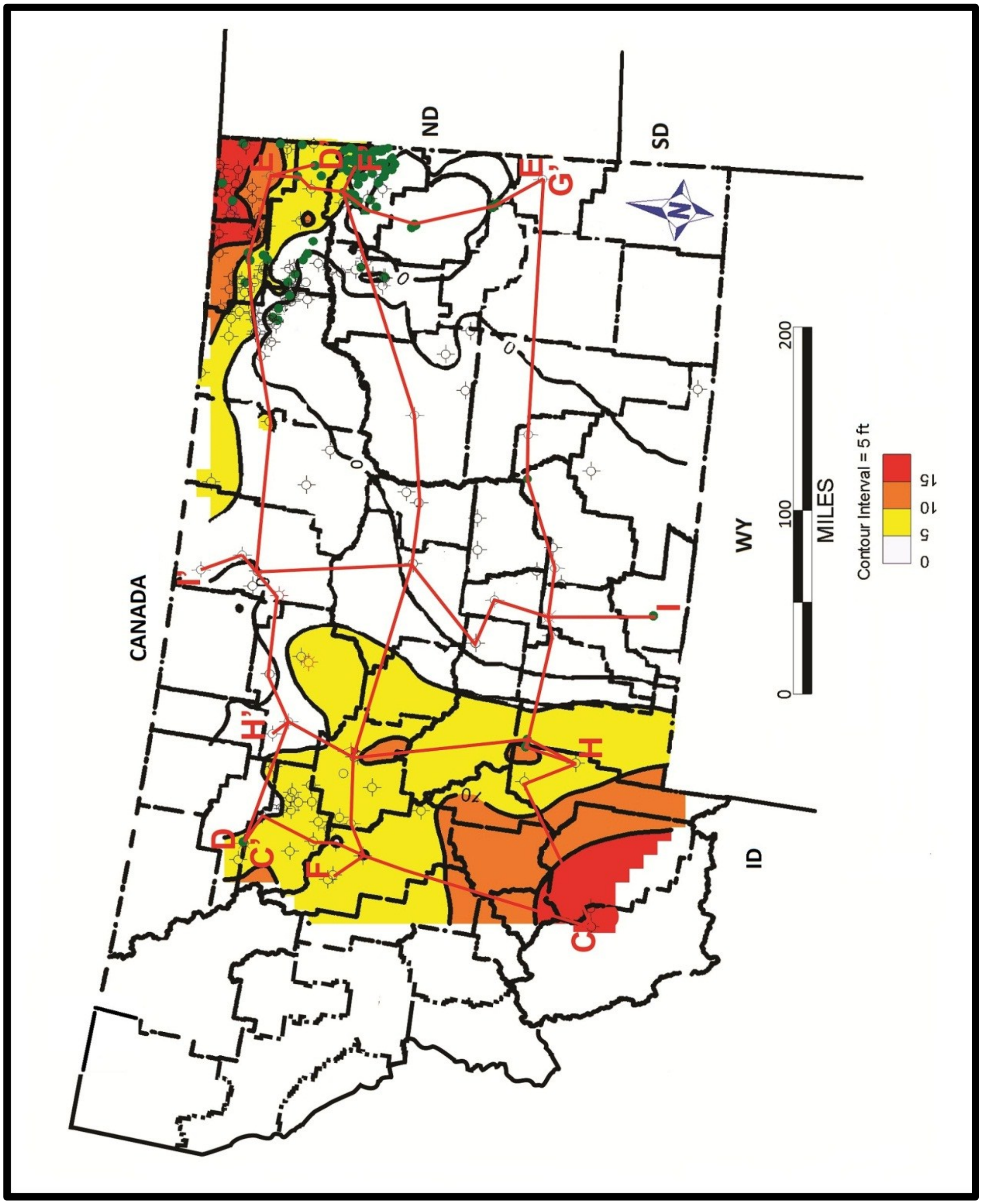

Figure 25. Thickness of the lower member of the Bakken/Sappington Formation.

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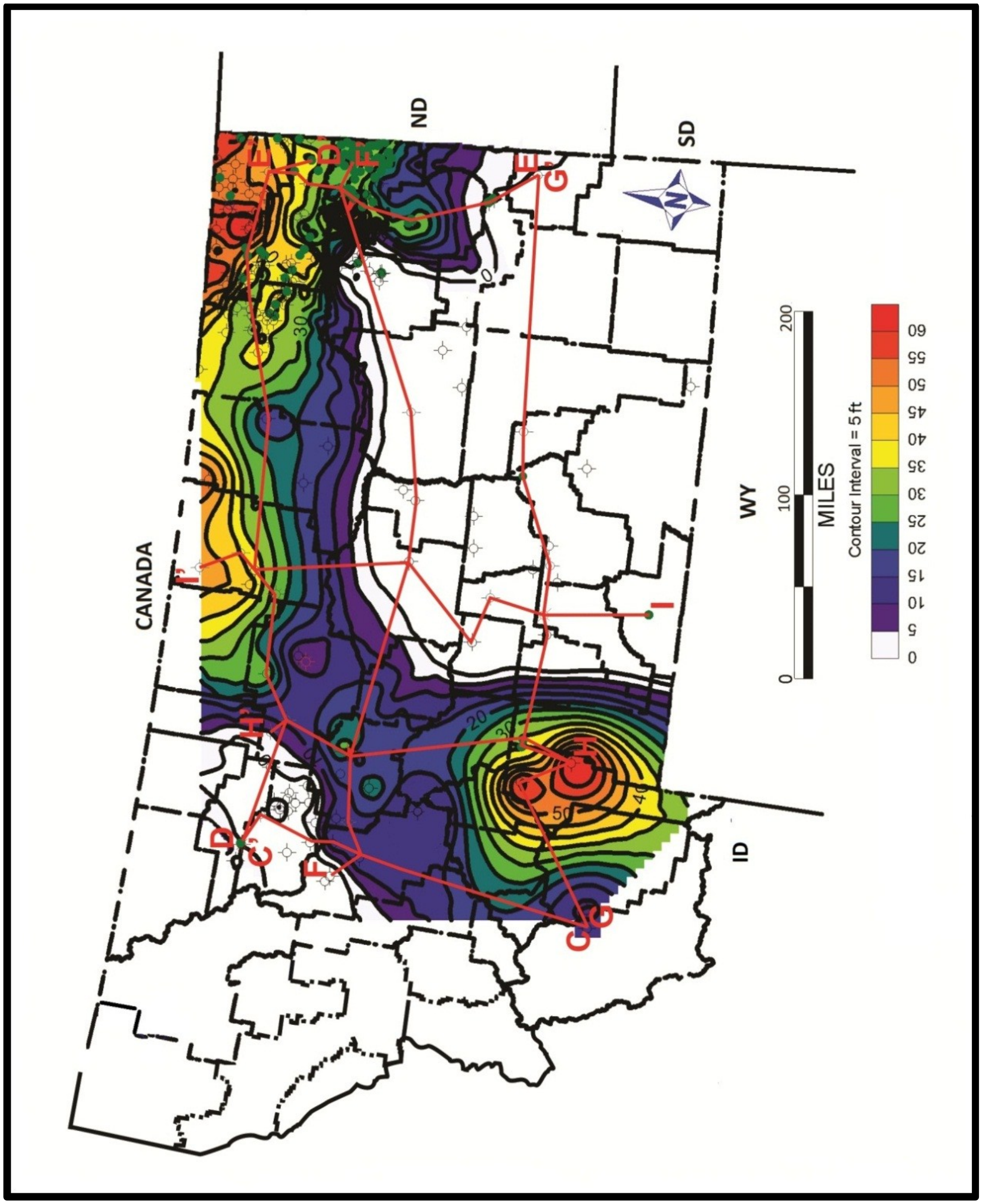

Figure 26. Thickness of the middle member of the Bakken/Sappington Formation.

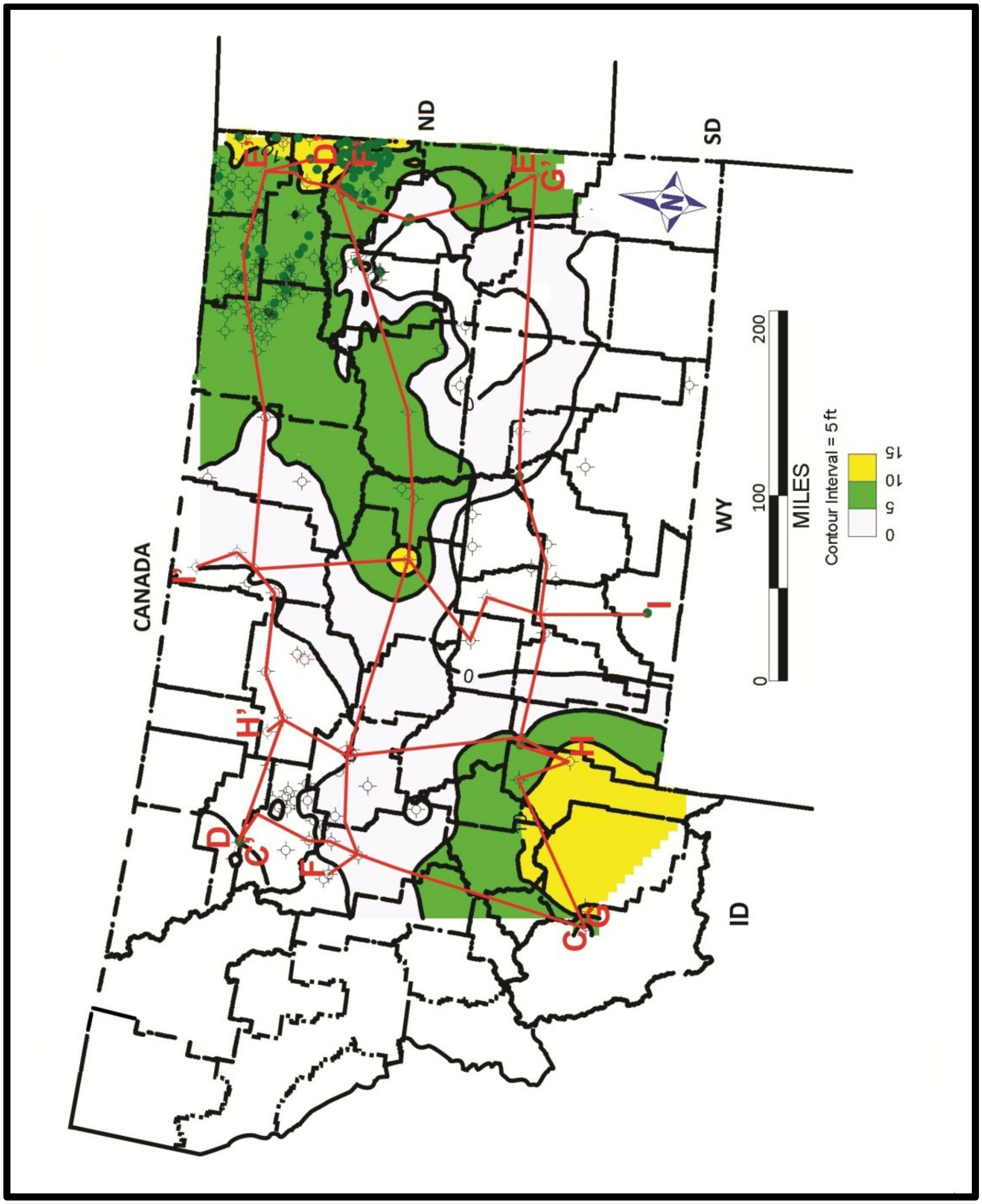

Figure 27. Thickness of the upper member of the Bakken/Sappington Formation.

4. DISCUSSION

Eustatic sea level rise and fall affected deposition of the Bakken/Sappington Formation throughout Montana. The Potlatch Anyhdrite Unit deposited during a stillstand (~8 m.y.) in northwestern Montana (Sandberg et al., 1982) and Fammenian transgression deposited and the upper Logan Gulch Member (The Gulch Knoll Limestone) of the Three Forks Formation in northwestern Montana (Sandberg, 1965; Sandberg et al., 1988). The Logan Gulch Member was then deposited in southwestern Montana, southern Alberta, and southwestern Saskatchewan (Sandberg, 1965). Then, another minor Fammenian transgression resulted in deposition of the Trident Member of the Three Forks Formation (Sandberg et al., 1982). The most widespread eustatic sea level rise in the late Fammenian resulted in deposition of the marine, basal black shales of the Bakken Formation in the Williston Basin and the Sappington Formation in the western Montana (Sandberg et al., 1988). Subsequent eustatic sea level fall at the end of the Fammenian resulted in deposition of the middle siltstone member of the Sappington/Bakken Formations. The upper member of the Bakken/Sappington Formation was deposited during the Early Mississippian marine transgression (Maughan, 1989). Although the depositional conditions of the lower and the upper members of the Bakken/Sappington Formation were similar, the distribution of these units is quite different across Montana (Figures 26-28).

The depositional environment of the Sappington Formation is generally similar to the Bakken Formation (Smith and Bustin, 1996; 2000; Angulo and Buatois, 2012; Egenhoff et al., 2011; Grau et al 2011). In cores, the Three Forks Formation and the three members of the Bakken Formation represent many different depositional environments, ranging from shallow water, coastal marine to deeper water, open marine settings (Christopher, 1961; Holland et al., 1987; LeFever et al., 1991; Smith and Bustin, 1996). The drastic juxtaposition of rocks deposited in such differing environments is caused by large eustatic sea level fluctuations during deposition of these units. The wave ripples, the trough cross laminations, and the bioturbation of the Three Forks Formation indicate marine influence and mark shallow intertidal environments in this unit. Following the deposition of the Three Forks Formation, sea level dropped that resulted in the erosion and unconformity on the basin flanks between the upper Three Forks Formation and Lower Bakken Member (Nordeng, 2009). Following erosion, eustatic sea level rose resulting in the marine transgression recorded by the deposition of the Lower Bakken Member (Smith, 1996).

The high organic content and the uniform dark gray-black color of the Lower Bakken Member indicate a change to stable anoxic bottom conditions following the oxic conditions of the Three Forks Formation (Webster, 1984; Smith and Bustin, 1995). Thin, planar laminations in the Lower Bakken Member indicate quiet water conditions below the storm base wave (Webster, 1984). The lag deposits at the base of the Lower Bakken Member record reworking of underlying sediments caused by bottom currents during the initial transgression across the unconformity surface (Smith and Bustin, 1995). The lag deposits in the Bakken Formation were deposited in shallow depressions or they accumulated on the protected sides of low relief obstructions due to winnowing of fine grained interstitial sediments (Huber, 1986).

The middle member of the Bakken/Sappington Formation was deposited in a moderate to well oxygenated coastal regime (Christopher, 1961; Pitman et al., 2001). The Middle Bakken Member is composed of multiple lithofacies recording deposition in many environments. Lithofacies A has no current or wave features and sparse bioturbation indicates and was deposited in an offshore marine setting between storm and fair weather wave base (Alexandre et al., 2011; Almanza, 2011). Lithofacies B is highly bioturbated siltstone with little or no current features recording deposition in the lower shoreface environment (Almanza, 2011; Alexandre et al., 2011). Lithofacies C is planar, subparallel, wavy, and small-scale cross-laminated interval with bioturbation indicating deposition of in a lower to upper shoreface setting with wave and tidal influences (Alexandre et al., 2011). Helmintophsis trace fossils and brachiopod remains indicate shallow infauna that lived in well oxygenated, normal-salinity bottom waters (Rowell and Grant, 1987; Pemberton et al., 1992; Smith and Bustin, 1996). The Teichicnus trace fossil formed in the Cruziana ichnofacies was deposited in a lower shoreface environment (Smith and Bustin, 1996). Planar, wavy, and small-scale cross laminations indicate deposition in lower, middle, to upper shoreface setting with wave and tidal influences (Alexandre et al., 2011). Lithofacies D is very thin sandy interval (less than 1 ft; 0.3 m thick) commonly included in Lithofacies C. Lithofacies E represents the lower intertidal environment with fair to moderate amount of bioturbation and some current and tidal features (Almanza, 2011; Alexandre et al., 2011). Lithofacies F records offshore subtidal marine deposition with an open name fauna and an increase in clay content (Almanza, 2011). In the cores, Lithofacies A, B and C are more continuous in Richland County and Williston Basin, and the other lithofacies occur locally or are absent in the basin.

The upper shale member of the Bakken Formation was deposited in a deep water environment (Sandberg et al., 1982; Webster, 1984; Ross and Ross, 1985) and there is an unconformity between the middle and the upper member. The lag deposit occurring locally at the base of this member includes coarse grain siliciclastic sediments, fish fragments, and pyrite. The organic content in the Upper Bakken Member is higher than in the Lower Bakken Member, due to higher biogenic activity in the water column that led to more accumulation of organic matter on the sea bottom (Smith and Bustin, 1996). The contact between the Upper Bakken Member and the Lodgepole Formation is conformable in the deeper part of the basin and unconformable on the basin flanks. Lodgepole Formation it composed of limestone that was deposited in a shallow, normal marine shelf environment (Heck et al., 2002)

The Bakken/Sappington deposition across Montana, including far east Williston Basin, was affected by the active paleohighs and troughs during Devonian-Mississippian time, which was related to a critical period of Antler Orogenesis (Dorobek et al., 1991). Antler Orogenesis played a significant role in the evolution of the North American Cordillera and the active paleostructures of Devonian-Mississippian time were oriented at high angles to the strike of the Antler Orogenic Belt (Dorobek et al., 1991).

The Bakken Formation in Montana is the thickest in the Sheridan, Roosevelt, and Richland Counties, where all three members were deposited there (compare Figures 17, 18, 19, and 24) near the Williston Basin depocenter which is located in North Dakota (east and south of the Nesson Anticline; LeFever, 1991). From Sheridan and Roosevelt Counties to the west and south of the Williston Basin in Montana, the Lower Bakken Member, and the Middle Bakken Member thin (compare Figures 18, 19, 25, and 26) (Sandberg, 1962), and only a thin Upper Bakken Member occurs on the basin flanks (compare Figures 18 and 27). This overall thinning in the Bakken Formation indicates the margins of the basin were active during the deposition of the Bakken Formation (LeFever et al, 2010). In the Latest Devonian, the margins of the Williston Basin were uplifted along the Cedar Creek Anticline which resulted in intense erosion, non-deposition or thin deposition of the Bakken Formation. The Bakken units show onlapping relationship and each succeeding covers a greater geographic extent than the underlying member (USGS, 2008). Hence, the Upper Bakken Member is the most widespread unit in the Williston Basin.

The Central Montana Uplift is one of the major structural features that was active during the Late Devonian (Sandberg et al., 1982). This uplift affected the distribution of the Bakken/Sappington Formation in central Montana as well as the Williston Basin. The Bakken/Sappington Formation is very thin or absent in Central Montana area due to the syntectonic Central Montana Uplift (Figures 19, 20, and 24). The total thickness of the Bakken/Sappington Formation (Figure 24) is less than 5 ft (1.5 m) thick or is absent at the Central Montana Uplift, because uplift of this structure stripped the Devonian strata from this area and caused these strata to be truncated around the uplift margins (Norwood, 1965). The truncation and thinning of the Devonian units over this uplift also explains the challenge in differentiating the Devonian Units in the subsurface of south central Montana. Below the clean gamma ray signature of the Lodgepole Formation, a relatively shaly unit is present (Figures 20 and 22), but it is difficult to determine its origin; it may be the middle member of the Bakken/Sappington or Three Forks Formation. Also, the lack of core and the limited number of the wireline logs in this region also make correlations difficult in this area. Thus, the base of the Lodgepole Formation is interpreted as the top of the Devonian (Figures 20 and 22) but the Bakken/Sappington Formation might be absent here due to syndepositional erosion along Central Montana Uplift.

The Central Montana Trough is important structural feature in Montana. It records increased Paleozoic subsidence (Maughan, 1993), and the Sappington Formation is well developed and is more than 70 ft (21.3 m) thick (compare Figures 16, 20, 21, and 24) However, toward northwestern Montana, significant thinning of the Bakken/Sappington Formation occurs (Figures 7, 16, 21, 24). The Upper and Middle Bakken/Sappington Member are not preserved in northwestern Montana, only the basal Bakken/Sappington Member occurs here (compare Figures 7, 16, 25, 26, and 27) (Sandberg and Mapel, 1967). Possibly the Upper and Middle Bakken/Sappington Member is absent in this area as a result of erosion and/or non-deposition associated with uplift of the Scapegoat-Bannatyne Anticline. To the east, the Middle and the Lower Bakken/Sappington Members may be present locally, but the Upper Bakken/Sappington Member was removed by Early Mississippian erosion of Bearpaw Anticline (Sandberg and Mapel, 1967). The Bakken/Sappington Formation also thins along the Yellowstone

Park Uplift. The Bakken/Sappington Formations thins from 80 ft to 5 ft (24.4-1.5 m (Figure 24) from the Central Montana Trough to the Yellowstone Park Uplift.

Even though the Bakken/Sappington Formation is well developed in the Central Montana Trough, the western part of this area has no upper shale, and the upper shale member appears to the east of the Central Montana Trough (Figure 8). Synsedimentary folds at the Milligan Canyon were responsible for the absence of the Upper Sappington Member here, as the erosive currents truncated Sappington Formation and no upper black shale was deposited (Adiguzel et al., 2012). Absence of this unit in parts of the western shelf suggests tectonic basin inversion in the western part of the Central Montana Trough (Adiguzel et al., 2012) related to a reversal of subsidence in this particular area (Visser, 1980; Ziegler 1987 a, b).

5. CONCLUSIONS

The Bakken Formation in the Williston Basin and the Sappington Formation in western Montana are coeval units whose deposition was affected by eustatic sea level rise and fall. Transgression deposited the Upper and Lower Bakken/Sappington Shale Members in deeper offshore marine settings and a rapid sea level drop deposited the middle member in multiple coastal regime environments.

The Bakken/Sappington formations are correlative across Montana, and the correlations indicate that there are remarkable thickness and distribution changes in these units. These thickness changes were produced by paleohighs and troughs that formed during deposition. The Central Montana Trough and the northeastern corner of the Montana (Montana part of the Williston Basin) record the thickest Bakken/Sappington, whereas thin areas coincide with the major uplifts such as the Yellowstone Park, Central Montana, Bearpaw, Scapegoat-Bannatyne Anticlines. The thinning around these structures may be related to nondeposition or erosion. The distribution of the Bakken/Sappington Members also is irregular across Montana. The Lower Bakken/Sappington Member is the most widespread unit in western Montana. However, it is absent in north central and central Montana due to the Bearpaw Anticline and the Central Montana Uplift. The Middle Bakken/Sappington Member is more than 50 ft (15.2 m) thick in southwestern Montana and it extends from southwestern to northwestern Montana. From northwestern to northeastern Montana its thickness ranges from 10 to 40 ft (3-12.2 m), but it is absent in far northwestern and central Montana due to erosion or non-deposition on the Scapegoat-Bannatyne Anticline and the Central

Montana Uplift. The Middle Bakken/Sappington Member may be a target for future oil and gas exploration, because it is less affected by the paleohighs, and it is the most continuous Bakken/Sappington Member across Montana. The Upper Bakken Member is widespread in the Williston Basin and eastern Montana. However, it is absent west of the Central Montana Trough, indicating basin inversion west of the Central Montana Trough occurred subsequent to deposition. The Upper Bakken/Sappington Member is absent in northwestern Montana due to erosion or non-deposition caused by the syndepositional uplift of the Bearpaw and Scapegoat-Bannatyne Anticlines.

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APPENDIX A

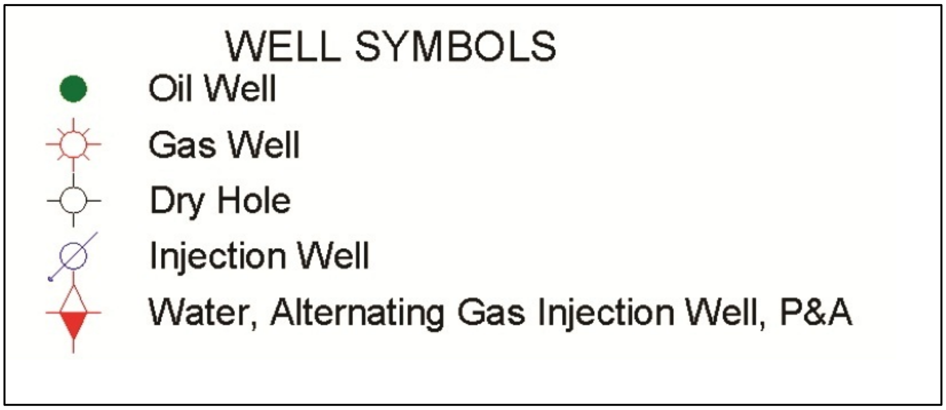

Figure 28. Well symbols used in isopach maps

APPENDIX B

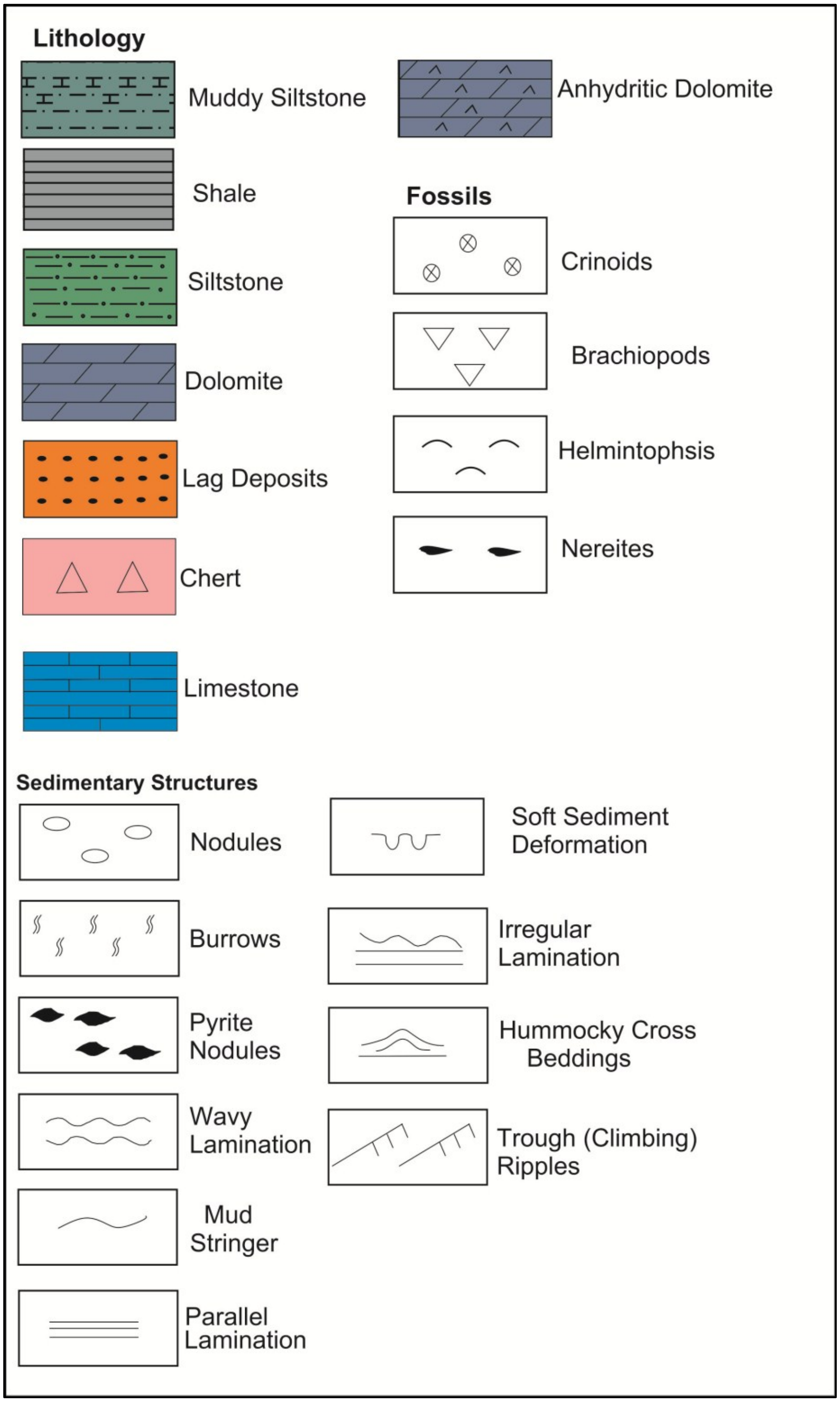

Figure 29. Legend of symbols used in core description.